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A NEW STUDY OF THE ANTHOPHYLLITE SERIES*†

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ABSTRACT

The composition and some physical properties of 96 varieties in the anthophyllite series are studied. Included is data on seven new anthophyllites from the pre-Beltian Cherry Creek rocks of Southwestern Montana. Chemical analyses, spectrographic analyses, optical properties, densities, and unit-cell structure are presented for the Montana varieties. Similar information is presented in part for 89 varieties described in the literature. *X*-ray

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structural studies are given for several doubtful varieties and some of these, such as amosite and high-manganese varieties from Bohemia, are shown to be monoclinic amphiboles. Main conclusions of the study are: 1. The anthophyllite and cummingtonite series are not isodimorphous. 2. The anthophyllite series is a 3-component one of limited isomorphism involving chiefly magnesium, iron, and aluminum. Iron (or Fe'' and Mn'') replaces magnesium from about 5% to about 50% of complete replacement calculated on the atomic basis. Aluminum replaces silicon nearly up to 2 atoms and the same is true of its replacement of Mg, Fe''; the formula $H_2Mg_5Al_2Si_6Al_2O_{24}$ is nearly fulfilled. 3. Magnanese is not important in the series. It is notable that many cummingtonites are high in manganese. Aluminum, high in many anthophyllites, is not a major constituent of the cummingtonite series. 4. Calcium is present in most anthophyllites, the average being about one-half of one per cent. About the same amount of sodium is present in many anthophyllites; potassium is present in negligible amounts in some anthophyllites and is absent in the rest. 5. The identification of anthophyllite is not certain unless based on *x*-ray methods. This is particularly true of asbestiform varieties.

The name anthophyllite should be used for all members of the series. Chemical suffixes as proposed by Schaller (1930) can be used to indicate any variation in composition if known. All synonyms, such as gedrite, amosite, picroamosite, and ferroanthophyllite, should be dropped.

The series can be characterized by the general formula $X_7Y_8O_{22}(OH, F)_2$ where X is chiefly Mg, Fe'', Al and in minor part Mn, Ti, Fe''', Ca, Na, K; Y is chiefly Si and in part Al. In X the maximum of Al is $(Mg, Fe'')_5Al_2$ and the maximum amount of Fe'' is about $(Mg_{3.5}\,Fe_{3.5})$. In Y the maximum amount of Al is (Si_6Al_2).

THE PROBLEM

The anthophyllite series, comprising the orthorhombic amphiboles and characterized in general by the formula $(Mg, Fe, Al)_7(Si, Al)_8O_{22}(OH, F)_2$, has long presented some fundamental problems to the mineralogist and petrologist. Although the simplest of the amphiboles, anthophyllite is complex enough in its chemical and physical properties so that no satisfactory study of the series has yet been achieved. A survey of the literature covering the period from the date of its first description (Schumacher 1801) to the present shows that it has been the subject of study by most of the better known mineralogists and petrologists of the times. However, much of the existing information is unsatisfactory. Many chemical analyses have been published without corresponding measurements of physical properties; many figures representing physical properties have been published without corresponding chemical analyses. In many studies, otherwise satisfactory descriptions of the chemical and physical properties are vitiated by an absence of paragenetic considerations.

One of the chief problems concerning the series is that of its relation to the chemically similar cummingtonite-grunerite series of the amphibole group. The varieties in this latter series are crystallographically monoclinic and the question is whether the two series are isodimorphous. In other words, is there complete isomorphism in the two series between the magnesium and the iron end members? If this were so, there should be a cummingtonite with a composition close to $Mg_7Si_8O_{22}(OH)_2$ and an anthophyllite with a composition close to $Fe_7Si_8O_{22}(OH)_2$ (disregarding aluminum, manganese, and fluorine). If the two series are not isodimorphous, what are the limits of replacement of Mg by Fe″ in the anthophyllites and of Fe″ by Mg in the cummingtonites?

Kunitz in his study of the amphibole group (1930) combined the anthophyllites and cummingtonites in one series. Winchell (1931) disagreed with this and separated the two series. In discussing the anthophyllites he wrote, "Unfortunately no member of this series very high in iron has been studied as yet . . . ."

Sundius (1933) decided that the anthophyllites and cummingtonites were not isodimorphous as no undoubted anthophyllites with more than 40% of the iron "molecule" and no cummingtonites with more than 60% of the magnesium "molecule" were known. Later Winchell (1938) published a further study of the two series. Primarily on the basis of two descriptions of high-iron anthophyllites by Orlov (1932) and Peacock (1928) he decided that the anthophyllite series was filled out to about 90% of the iron end member. He concluded that, "Perhaps the most important conclusion to be derived from these studies is that the anthophyllite and cummingtonite series actually illustrate a case of isodimorphism, since the cummingtonite series extends beyond 60 numerical per cent of $H_2Mg_7Si_8O_{24}$ and the anthophyllite series extends at least to about 90 numerical per cent of $H_2Fe_7Si_8O_{24}$."

Collins (1942) in a short discussion of the correlation of optical properties and chemical composition in the two series concluded that Kunitz and Winchell (and Alling) were " . . . wrong in their belief that cummingtonite, anthophyllite, and gedrite form one homogeneous series."

The soundness of Winchell's conclusion of 1938 depends mainly on the validity of the so-called high-iron anthophyllites. The varieties described by Orlov and Peacock are asbestiform and the identification of such material by optical means is not satisfactory. As no *x*-ray diffraction studies of these specimens had been made their identification as anthophyllite could be questioned.

The importance of aluminum in the anthophyllite series has not been adequately considered by previous workers. Magnesium and iron have been thought to be the main variables but a cursory survey of anthophyllite analyses shows that alumina occurs in amounts greater than 10% in many varieties. This raises the question as to whether the series might not be best represented with three main variables, magnesium, iron, and aluminum.

A further question concerns the identification of anthophyllite in general. If the identification is based on optical methods alone many amphiboles might be determined as anthophyllite when they are really cummingtonite, tremolite, actinolite, or other monoclinic members. Also, the orthorhombic pyroxenes can be wrongly identified as anthophyllite and vice versa. A combination of optical and chemical determinations does not uniquely determine all varieties of anthophyllite; some would be confused with cummingtonite. It remains, then, to determine the proper method or methods for the identification of anthophyllite.

These questions and others which will be apparent in succeeding pages show that it is desirable to make a new study of the series. This paper is an attempt at such a study.

As a framework the properties of seven new varieties from the pre-Beltian Cherry Creek series of southwestern Montana are described.

This data* is combined with that from the literature to form the basis for answers to the problems outlined. Finally, a revision of the series is proposed and suggestions are made for further work.

NOMENCLATURE AND CLASSIFICATION

Anthophyllite was first described and named by Schumacher (1801). Schumacher's material came from near Kongsberg, Norway, and because of its clove-brown color he named it after the Greek word for clove, anthophyllum. The name was continued by other authors up to 1819. In succeeding years new synonyms were introduced such as *anthogrammit* (Breithaupt 1820), *prismatic schiller-spar* (Jameson 1821), *anthophyllite rayonne* (Haüy 1822), *antholite* (Breithaupt 1830), and *gedrite* (Dufrénoy 1836). None of these survived except gedrite which had been introduced by Dufrénoy for what he regarded as a new species from Gèdres in the Pyrenees. In later years as more analyses of gedrite were made and its physical properties determined it was seen that it was an aluminian variety of anthophyllite and the name is widely used today in that sense.

In Dana's first edition of his *System* (1837) the term *augitus phyllinus* was used but in the third edition (1850) the name was dropped and gedrite and anthophyllite were listed as varieties of hornblende.

The name *kupfferite* was introduced by Hermann (1862) to designate an amphibole similar to anthophyllite in composition but monoclinic in form. The original material came from a graphite mine in the Tunkinsk Mountains of Russia and was apparently a chromian amphibole. Similar material from near Miask in the Ilmen Mountains was used for the analysis establishing the composition of the mineral. The name has since been used as a synonym for anthophyllite because it was later assumed that the original material was orthorhombic. After this the original material was again shown to be monoclinic and the name was then given to the magnesium end member of the cummingtonite series. However, no such end member has been found and to end all this confusion it would be best for the name to be dropped.

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* The word "data," unavoidably appearing so often in this report as in much of scientific writing, is used in this paper as a collective noun in the singular. The singular equivalent of data, datum, is rarely if ever used in the sciences in the sense of a single fact and it would seem to me appropriate for scientists to switch to "data is" in place of "data are." There is ample American precedent by analogy for such usage.

After 1862 new synonyms proposed were *snarumit* (Breithaupt 1865), *thalackerite* (Breithaupt; see Des Cloiszeaux 1868), *valléite* (Cesàro 1895, 1896), *ferroanthophyllite* (Shannon 1921), *amosite* (Hall 1918; Peacock 1928), and *picroamosite* (Serdiuchenko 1936).

Of these names, ferroanthophyllite assumed immediate importance. Shannon included a note on the nomenclature of the anthophyllite series as follows:

> Palmgren in 1917 found a similar amphibole in the eulysite of Södermannland, Sweden. . . . Palmgren also emphasizes the fact that this amphibole is distinct from anthophyllite, but, following Warren, whom he cites, he used the name eisenanthophyllite, which becomes iron anthophyllite in English. The present writer prefers the form ferroanthophyllite as the name for the iron end member of the anthophyllite group despite the fact that the magensium end member will then require the rather unwieldy name magnesioanthophyllite. This nomenclature is in accord with that recently used by American mineralogists to designate end members of isomorphous groups. The group name anthophyllite will then indicate intermediate mixtures of the two end members of the series, while the name gedrite will continue to indicate important admixture of the aluminous molecule. The possibility of occurrence of lime and manganese members of this series is remotely indicated.

In citing C. H. Warren, Palmgren had reference to Warren's description (1902) of a nearly pure iron anthophyllite from Rockport, Massachusetts. Material similar to that of Palmgren was described by Eckermann (1922) as occurring in the Mansjö Mountain, Sweden. It is interesting that all of this so-called high-iron anthophyllite, including that of Shannon, is either hypersthene (Palmgren's and Eckermann's), grunerite (Warren's), or actinolite (Shannon's).

Peacock (1928), in a study of amosite, decided that that material was high-iron orthorhombic amphibole. The name had been proposed by Hall (1918) for the ash-gray asbestos occurring in the Transvaal of Africa. Wherry (1921) found that it had what he considered to be the optical properties of ferroanthophyllite and he decided that amosite comprised both grunerite and ferroanthophyllite.

From his optical and chemical study Peacock concluded that:

> Amosite evidently belongs to the orthorhombic amphiboles; but on account of the intermediate amount of sesquioxides carried by this mineral, and the fact that these constituents apparently link themselves partly in the subvalent gedrite manner and partly with full valency, amosite cannot be properly identified either with anthophyllite, ferroanthophyllite or gedrite. And therefore, if we are justified in retaining crocidolite, which differs from riebeckite only in its fibrous structure, then there are even better grounds for retaining amosite as a mineral species.

Strunz in his study of the silicates (1938) regarded amosite as monoclinic.

Picroamosite (containing 8.28% Fe_2O_3) was proposed as a new name by Serdiuchenko because "it is evidently a magnesial analogue of the amosite, because MgO is almost exclusively represented in the same, and not FeO as in the amosite, therefore the author has named it picroamosite." Serdiuchenko postulated two branches of the isomorphous range in the anthophyllite series, (a) ferroanthophyllite—amosite—gedrite, and (b) magnesioanthophyllite—picroamosite—ferrigedrite.

In the meantime, *Dana's* sixth edition (1892) listed anthophyllite as an orthorhombic amphibole (Dana no. 337) and gedrite was listed as an "aluminous" variety.

Berman (1937) in his important work on the constitution and classification of the natural silicates listed anthophyllite and gedrite as names to be used in the anthophyllite series of the amphibole group.

Winchell (1938) proposed, for the orthorhombic amphiboles, that, "the whole system may be called anthophyllite, the pure magnesian end-member being called magnesioanthophyllite (or maganthophyllite), the pure iron end-member ferroanthophyllite (or feranthophyllite), the high-alumina types gedrite and the high soda antholite." This last name, he said, had been applied to anthophyllite asbestos but he thought that the few available analyses suggested that this variety was always high in soda. Kupfferite, as the name applying to the nearly pure magnesian end member in the cummingtonite series, he said was so far unknown in nature.

Changing views as to the formula to be applied to anthophyllite can be shown by the following formulas in the six editions of *Dana's System:*

First (1837) —3 parts of bisilicate of magnesia
1 part of bisilicate of iron
Second (1844)—None
Third (1850) —$\dot{\mathrm{Fe}}\ \dddot{\mathrm{Si}} - \mathrm{Mg}^3\ \dddot{\mathrm{Si}}^2$
Fourth (1854)—$\dot{\mathrm{Fe}}\ \dddot{\mathrm{Si}} - \mathrm{Mg}^3\ \dddot{\mathrm{Si}}^2$
Fifth (1868) —$\dot{\mathrm{Fe}}\ \dddot{\mathrm{Si}} - 3\ \dot{\mathrm{Mg}}\ \dddot{\mathrm{Si}}$
Sixth (1892) —$(Mg, Fe)\ SiO_3$

The formula $(Mg, Fe)\ SiO_3$ was generally accepted as correct until Warren's *x*-ray study (1930) showed that water was a necessary part of the structure. That this was true for tremolite had been proposed by Schaller in 1916. Penfield (1890) and Coblentz (1911) had come earlier to similar conclusions for anthophyllite and tremolite.

On the basis of his *x*-ray study Warren proposed the formula $H_2Mg_7(SiO_3)_8$. A more general one, showing the isomorphism in the series, was adopted by Berman:

$$X_7(Z_4O_{11})_2(OH)_2$$
where X = Mg, Fe, Mn, Al in part
Z = Si principally and Al in part

Specifically, this becomes $(Mg, Fe)_7Si_8O_{22}(OH)_2$ for anthophyllite and $(Mg,Fe,Al)_7(Al,Si)_8O_{22}(OH)_2$ for gedrite. It should be emphasized that by this scheme Al can replace Si up to a limit of 2 atoms and it can replace Mg and Fe also up to a limit of 2 atoms. The formula for such a maximum replacement would be $(Mg,Fe)_5Al_2(Si_6Al_2)O_{22}(OH)_2$. Also, OH can be replaced by F.

According to Berman, the cummingtonite series has the same general formula as that of anthophyllite. Specifically, also, the formulas are the same except that grunerite is $(Mg,Fe,Mn)_7Si_8O_{22}(OH)_2$.

These can be contrasted with the formulas given for tremolite $Ca_2Mg_5Si_8O_{22}(OH)_2$ and actinolite $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$.

Such is the status of the nomenclature and classification of the anthophyllite series as it appears in the literature.

Chemical Analyses

Ninety-six chemical analyses are given, seven of them new. The 89 from the literature are all that I have been able to find, from John's in 1904 to the present. They show all degrees of accuracy and the material on which they were made no doubt covered a wide range of impurity. In general, analyses of a later date were more accurate, and the material purer, than those made earlier. This dictum is subject to exceptions; the analysis of Penfield (1890) is better than some made in the last fifteen years. It cannot be emphasized too strongly that a good analysis is wasted on impure material. Such a statement is axiomatic but even in late years there have been too many instances of such a waste of a chemist's time. It is hard to determine now the purity of the material used in the earlier analyses but the inference is that much of it was not pure enough for good analytical results. Standard practice today demands that material submitted for analysis be examined microscopically and re-cleaned if the purity is less than 99%. A good description of such practice is in Eskola (1936) and in Collins (1942).

All of the analyses are shown in tables 2 to 6 arranged in each table in order of increasing silica content. They are numbered consecutively and wherever an analysis, or the anthophyllite it represents, is discussed in this study it will be referred to by that number. The seven new analyses on specimens from Montana are numbered 1, 8, 9, 14, 17, 29, and 30. They are shown separately in table 1 and are repeated in table 2.

Table 1. Chemical Analyses of Montana Anthophyllites
Forest Gonyer, *analyst*

	1. (CC206F)	8. (CC298)	9. (Mont.40-12)	14. (CC121)	17. (CC352C)	29. (CC200A)	30. (Mont.40-8)
SiO_2	42.80	45.41	45.98	48.49	50.36	57.02	57.14
TiO_2	.49	.44	.53	.41	.43	None	Trace
Al_2O_3	17.78	15.84	14.92	13.26	8.06	1.40	1.94
Fe_2O_3	1.03	2.94	.62	1.28	2.18	None	None
FeO	18.32	15.32	17.42	14.60	18.36	8.71	11.12
MnO	.14	.07	.04	None	None	.09	.11
MgO	15.54	17.60	18.27	20.56	17.57	28.81	26.82
CaO	None	.14	.07	.04	.74	1.48	.64
Na_2O	1.52	.28	.47	.11	.70	.66	.27
K_2O	.03	None	None	None	None	None	.06
F	.31	None	None	None	None	None	None
H_2O+	1.94	1.84	1.51	1.48	1.69	1.59	2.06
	99.90						
$0=F_2$	.13						
	99.77	99.88	99.83	100.23	99.99	99.76	100.16

These varieties occur in the rocks of the pre-Beltian Cherry Creek Series of southwestern Montana as follows:

1. Cherry Creek Area, Madison Co., Montana. In amphibolite with garnet, quartz, plagioclase, and rutile.
8. Cherry Creek area, Madison Co., Montana. In amphibolite with garnet, quartz, plagioclase, and staurolite.
9. Dillon Complex, Beaverhead Co., Montana. In schist bordering a metamorphosed ultramafic body (Dillon Complex) with quartz, feldspar, and spinel.
14. Ruby Dam Area, Madison Co., Montana. In amphibolite with garnet, quartz, plagioclase, chlorite, and rutile.
17. Cherry Creek Area, Madison Co., Montana. Same association as No. 1.
29. Cherry Creek Area, Madison Co., Montana. In isolated boulders with chlorite.
30. Dillon Complex, Beaverhead and Madison Counties, Montana. In the ultramafic body with actinolite, serpentine, enstatite, clinohumite, spinel, annabergite, and magnetite.

The original specimens have been deposited in the collection of the Department of Mineralogy at Harvard University and duplicates will be given to the U. S. National Museum. Thus the numbering system for these specimens is as follows:

Analysis No.	Field No.	Harvard No.	U.S.N.M. No.
1	CC206F	97574	105352
8	CC298	97575	105353
9	Mont.40-12	97576	105354
14	CC121	97577	105355
17	CC352C	97578	105356
29	CC200A	97579	105357
30	Mont.40-8	97580	105358

TABLE 2. SELECTED MODERN ANALYSES OF ANTHOPHYLLITE, 1890–1946

A.—Chemical weight per cent; A is weight per cent $MgO+CaO+Na_2O+K_2O$, B is weight per cent $FeO+Fe_2O_3+MnO+TiO_2$, and C is weight per cent of Al_2O_3 where A+B+C equal 100 per cent

No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	F	H_2O-	H_2O+	Total	$FeO+Fe_2O_3+MnO+TiO_2$	A	B	C
1	42.80	.49	17.78	1.03	18.32	.14	15.54	None	1.52	.03	.31	—	1.94	99.90	19.98	31.2	36.4	32.4
2	43.70	.55	10.88	3.52	26.53	.24	11.48	.54	1.24	.15	—	—	1.21	100.04	30.84	24.4	55.9	19.7
3	44.09	.31	17.22	1.87	15.02	.14	17.12	.51	1.24	tr	—	.29	2.03	99.55	17.34	35.3	32.2	32.5
4	44.22	—	23.79	.20	9.21	.11	20.69	—	—	—	—	—	1.42	100.31	9.37	38.3	17.7	44.0
5	44.32	—	16.04	2.80	16.88	.09	15.95	.77	——1.86——		—	—	1.31	100.02	19.77	34.1	36.3	29.5
6	44.70	.57	14.72	1.62	18.96	.21	14.89	.69	1.34	None	—	.29	2.27	100.26	21.36	32.0	40.3	27.7
7	45.38	—	14.70	.94	18.14	.31	15.26	.62	1.20	.19	—	.23	2.77	99.74	19.39	33.6	37.7	28.7
8	45.41	.44	15.84	2.94	15.32	.07	17.60	.14	.28	None	None	—	1.84	99.88	18.77	34.2	35.7	30.1
9	45.98	.53	14.92	.62	17.42	.04	18.27	.07	.47	None	None	—	1.51	99.83	18.66	36.0	35.5	28.5
10	46.50	.89	15.48	.89	16.01	None	17.62	.81	.77	.12	—	—	1.19	100.28	17.79	36.7	33.9	29.4
11	47.24	—	9.63	—	21.29	2.70	15.62	1.16	.35	—	—	—	2.31	100.30	23.99	33.8	46.3	19.9
12	47.86	.63	14.09	.33	14.41	.14	19.89	.57	.93	.06	—	None	2.46	100.42	13.88	43.4	28.1	28.5
13	48.00	1.00	7.63	1.11	26.11	.18	12.66	.64	1.21	.24	—	—	1.09	99.87	28.40	29.1	55.9	15.0
14	48.49	.41	13.26	1.28	14.60	None	20.56	.04	.11	None	None	—	1.48	100.23	16.29	41.2	32.4	26.4
15	49.66	—	6.74	1.23	18.09	.05	18.62	3.38	—	—	—	—	1.56	99.33	19.37	45.7	40.3	14.0
16	50.10	.73	7.35	None	22.18	.25	16.64	.60	.54	None	—	—	1.15	99.63	23.16	36.8	48.0	15.2
17	50.36	.43	8.06	2.18	18.36	None	17.57	.74	.70	None	None	—	1.69	99.99	20.87	39.7	43.5	16.8
18	51.06	—	1.90	1.22	24.81	2.03	16.41	.52	—	—	—	—	2.14	100.09	28.06	36.1	59.9	4.0
19	51.62	—	10.32	1.94	3.72	.87	26.82	1.29	.32	.68	—	—	2.23	99.81	6.53	63.3	14.2	22.5
20	52.26	1.11	10.35	4.31	17.13	—	12.52	—	—	—	—	—	2.00	99.68	22.55	27.6	49.6	22.8
21	52.48	.05	4.35	7.03	9.02	—	25.06	.14	—	—	.2	—	2.00	100.39	16.10	55.6	35.1	9.3
22	53.93	.02	1.79	1.84	20.50	.25	18.92	.12	.15	.07	.5	—	2.08	100.19	22.61	44.1	51.8	4.1
23	55.20	.06	2.83	3.43	8.11	—	28.46	.76	—	—	—	.14	1.27	100.26	11.60	67.0	26.5	6.5
24	55.34	—	2.56	—	15.29	.51	22.80	.63	.19	.12	—	—	2.34	99.78	15.80	56.4	37.5	6.1
25	55.90	None	1.13	8.28	.68	.49	29.26	.94	None	None	—	—	3.20	99.88	9.45	74.1	23.2	2.7
26	55.97	—	.59	1.46	15.38	.48	23.04	.37	.11	.03	.4	—	2.33	100.21	17.32	56.8	41.8	1.4
27	56.27	—	2.07	.40	13.81	.59	23.99	1.15	—	—	—	—	1.83	100.11	14.80	59.9	35.2	4.9
28	56.40	—	1.15	—	11.40	—	28.68	.50	—	—	—	—	1.63	99.76	11.40	69.9	27.3	2.8
29	57.02	None	1.40	None	8.71	.09	28.81	1.48	.66	None	None	—	1.59	99.76	8.80	75.2	21.4	3.4
30	57.14	tr	1.94	None	11.12	.11	26.82	.64	.27	.06	None	—	2.06	100.16	11.23	68.8	26.6	4.6
31	57.19	—	.92	—	7.98	.28	28.03	.76	—	—	—	.48	3.83	99.59	8.26	75.8	21.8	2.4
32	57.46	tr	.79	.81	13.21	.50	24.44	.32	——.14——		—	.06	2.58	100.62	14.52	62.0	36.0	2.0
33	57.60	—	1.94	1.58	6.62	—	30.32	tr	—	—	—	.20	2.66	100.92	8.20	75.0	20.3	4.7
34	57.86	—	2.46	.63	5.96	.33	29.38	.86	.41	—	—	—	2.45	100.34	6.92	76.6	17.3	6.1
35	57.98	—	.63	—	10.39	.31	28.69	.20	—	—	—	.12	1.67	99.99	10.70	71.8	26.6	1.6
36	58.03	—	—	4.87	5.95	—	28.57	—	1.12	.19	—	.17	1.20	100.10	10.82	73.4	26.6	—
37	58.38	—	.10	—	8.37	—	28.82	.61	—	—	—	.68	2.75	99.71	8.27	77.6	22.1	.3
38	58.43	tr	.10	.72	6.84	.12	29.66	tr	tr	tr	—	.16	3.76	99.79	7.68	79.2	20.5	.3
39	58.74	.02	.12	.66	5.61	.06	29.95	tr	tr	tr	—	.24	4.59	99.99	6.35	82.2	17.4	.4
40	58.75	—	1.27	—	5.60	—	31.53	—	.51	—	—	.25	1.70	99.61	5.60	82.3	14.4	3.3
41	58.82	—	.66	.52	—	2.53	30.81	3.45	—	—	.28	—	2.64	99.93	3.05	90.2	8.1	1.7
42	59.12	—	.91	1.01	6.89	.23	29.67	.06	.30	—	—	—	1.97	100.16	8.13	76.9	20.8	2.3
43	59.29	.03	.59	.29	.06	2.77	30.98	1.26	.37	.19	.20	—	3.80	99.83	3.15	89.8	8.6	1.6
44	59.56	—	.66	.76	7.49	.17	28.97	—	—	—	—	.31	2.38	100.30	8.32	76.1	22.1	1.8
45	59.60	—	5.72	.84	3.24	.01	27.94	.22	.12	.04	—	—	2.27	100.00	4.09	74.3	10.7	15.0
46	60.16	tr	.39	.50	5.88	.05	29.04	None	——.33——		—	.21	2.72	100.14	6.43	81.1	17.8	1.1

1. Deduct .13 for $O=F_2$
12. All TiO_2 is rutile; $P_2O_5=.05$
16. $V_2O_3=.09$
20. Average of two analyses
21. Deduct .12 for $O=F_2$
22. Deduct .22 for $O=F_2$
26. Deduct .19 for $O=F_2$
31. $Cr_2O_3=.12$
32. Vol.=.21; $CO_2=.10$; $Cr_2O_3=$tr.
37. Average of 3 analyses
38. $P_2O_5=.00$
39. $P_2O_5=.00$
41. Deduct .12 for $O=F_2$
43. Deduct .08 for $O=F_2$
45. Average of 2 analyses recalculated to 2(OH)

B.—Number of atoms of ent based on the general anthophyllite formula (Mg, Fe″, Fe‴, Mn, Ti, Al)$_7$ (Si, Al) O_{22} (OH, F)$_2$ with minor of (Ca, Na, K) which is one-fourth the content of the unit cell. Col. A is the ratio of aluminum replacing silico aluminum plus ferric iron replacing magnesium, etc. Col. B is the atomic per cent of Fe″ Mn+Ti where Mg+Fe″+Fe‴+Mn+Ti+Al(1) equal 100 per cent

No.	Ca	Na	K	M	F‴	Mn	Ti	Al(1)	Total	Si	Al	Total	OH	F	O	A	B
1	—	.41	—	3.	.10	.02	.05	1.24	7.40	6.20	1.80	8.00	1.86	.14	22.00	1.34	35.6
2	.09	.37	.02	2.	.40	.03	.06	.63	7.60	6.68	1.32	8.00	1.22	—	22.78	1.28	51.0
3	.08	.32	—	3.	.20	—	.03	1.20	7.28	6.30	1.70	8.00	1.92	—	22.08	1.21	27.6
4	.09	—	—	4.	.01	.01	—	1.91	7.31	6.07	1.93	8.00	1.30	—	22.70	1.00	16.6
5	.12	.43	—	3.	.31	.01	—	1.18	7.58	6.44	1.56	8.00	1.25	—	22.75	1.04	31.2
6	.11	.36	—	3.	.17	.03	.06	.97	7.21	6.47	1.53	8.00	2.19	—	21.81	1.34	35.1
7	.09	.32	.03	3.	.10	.03	—	.99	7.00	6.51	1.49	8.00	2.63	—	21.37	1.36	32.6
8	.01	.07	—	3.	.31	—	.04	1.16	7.20	6.50	1.50	8.00	1.75	—	22.25	1.02	30.2
9	—	.12	—	3.	.07	—	.05	1.11	7.24	6.60	1.40	8.00	1.43	—	22.57	1.18	30.5
10	.12	.10	—	3.	.10	—	.09	1.24	7.30	6.64	1.36	8.00	1.13	—	22.87	1.01	27.6
11	.17	.09	—	3.4	—	.33	—	.56	7.16	6.91	1.09	8.00	2.25	—	21.75	1.94	40.7
12	.08	.25	—	4.1	.02	.02	—	.99	7.09	6.68	1.32	8.00	2.28	—	21.72	1.30	22.6
13	.10	.34	.04	2.8	.12	.02	.11	.62	6.88	7.26	.74	8.00	1.09	—	22.91	1.00	47.2
14	—	.02	—	4.3	.13	—	.04	1.01	7.25	6.82	1.18	8.00	1.39	—	22.61	1.03	25.9
15	.50	—	—	4.0	.14	—	—	.48	7.39	7.25	.75	8.00	1.51	—	22.49	1.20	31.8
16	.10	.14	—	3.6	—	.02	.08	.65	7.39	7.38	.62	8.00	1.11	—	22.89	.95	38.1
17	.11	.18	—	3.6	.24	—	.04	.31	6.67	7.01	.99	8.00	1.55	—	22.45	1.80	35.8
18	.08	—	—	3.6	.14	.25	—	—	7.18	7.58	.34	7.92	2.12	—	21.88	2.42	48.1
19	.19	.08	.12	5.4	.20	.10	—	.63	7.18	6.99	1.01	8.00	2.00	—	22.00	1.21	9.9
20	—	—	—	2.6	.46	—	.23	1.14	6.52	7.42	.58	8.00	1.89	—	22.11	.36	41.6
21	.02	—	—	5.2	.73	—	—	—	7.01	7.29	.69	7.98	1.85	.15	22.00	.94	25.2
22	.01	.03	—	4.0	.19	.02	—	.08	6.88	7.77	.23	8.00	1.99	.24	21.77	.85	38.8
23	.10	—	—	5.9	.34	—	—	.08	7.36	7.64	.36	8.00	1.16	—	22.84	.85	17.3
24	.09	.05	.02	4.7	—	.06	—	.17	6.97	7.75	.25	8.00	2.18	—	21.82	1.47	26.5
25	.13	—	—	5.8	.83	.06	—	—	6.95	7.47	.18	7.65	2.83	—	21.17	.21	14.4
26	.05	.03	—	4.8	.15	.06	—	—	6.91	7.83	.10	7.93	2.16	.20	21.64	.66	28.9
27	.16	—	—	5.0	.05	.07	—	.19	7.10	7.86	.14	8.00	1.68	—	22.32	.58	24.3
28	.07	—	—	5.9	—	—	—	—	7.34	7.81	.18	7.99	1.49	—	22.51	—	17.9
29	.21	.16	—	5.9	—	.01	—	.08	7.40	7.85	.15	8.00	1.42	—	22.58	1.87	13.5
30	.09	.06	.01	5.5	—	.01	—	.15	7.09	7.84	.16	8.00	1.88	—	22.12	1.06	17.9
31	.10	—	—	5.6	—	.03	—	—	6.67	7.69	.15	7.84	3.42	—	20.58	—	13.7
32	.04	.03	—	5.0	.08	.04	—	.06	6.81	7.93	.07	8.00	2.35	—	21.65	.50	23.3
33	—	—	—	6.0	.16	—	—	—	6.95	7.36	.30	7.66	2.35	—	21.65	1.87	12.5
34	.12	.10	—	5.8	.06	.03	—	.14	7.00	7.74	.26	8.00	2.18	—	21.82	1.30	10.7
35	.03	—	—	5.91	—	.04	—	.06	7.22	7.96	.04	8.00	1.53	—	22.47	.66	16.9
36	—	.30	.03	5.89	.49	—	—	—	7.39	7.98	—	7.98	1.09	—	22.91	—	15.8
37	.09	—	—	5.86	—	—	—	—	6.90	7.92	.02	7.94	2.44	—	21.56	—	13.7
38	—	—	—	5.92	.06	.01	—	—	6.74	7.77	.02	7.79	3.32	—	20.68	.33	12.2
39	—	—	—	5.88	.06	—	—	—	6.56	7.71	.02	7.73	4.01	—	19.99	.33	10.4
40	—	.06	—	6.38	—	—	—	.13	7.20	7.92	.08	8.00	1.52	—	22.58	.63	8.7
41	.49	.05	—	6.13	.05	.28	—	—	7.00	7.80	.11	7.91	2.32	.12	21.56	2.20	4.7
42	.01	.06	—	5.99	.10	.02	—	.11	7.06	7.96	.04	8.00	1.76	—	22.24	.19	12.7
43	.18	.10	.03	6.04	.03	.31	—	—	6.70	7.76	.09	7.85	3.32	.08	20.60	3.00	5.2
44	—	—	—	5.83	.06	.02	—	.10	6.84	8.00	—	8.00	2.13	—	21.87	—	13.5
45	.03	.03	—	5.50	.08	—	—	.71	6.70	7.83	.17	8.00	2.00	—	22.00	2.12	6.4
46	—	.06	—	5.8	.05	—	—	.06	6.67	8.05	—	8.05	2.42	—	21.58	—	10.7

No.	Date	Author	Locality	Analyst
1	1948	Rabbitt	Cherry Creek Area, Madison Co., Montana	Forest Gonyer
2	1936	Eskola	Isopää, Kalvola, Finland	Tauno Kervinen
3	1939	Tilley	Karelia, U.S.S.R.	H. C. G. Vincent
4	1931	Henderson	Masons Creek, Franklin Co., North Carolina	E. P. Henderson
5	1908	Evans and Bancroft	Haliburton Co., Ontario, Canada	N. N. Evans
6	1942	Collins	Sutherland, England	Geochemical Laboratories
7	1931	Simpson	Bullsbrook, Western Australia	D. G. Murray
8	1948	Rabbitt	Cherry Creek Area, Madison Co., Montana	Forest Gonyer
9	1948	Rabbitt	Dillon Complex, Beaverhead Co., Montana	Forest Gonyer
10	1934	Ignatiev	Karelia, U.S.S.R.	Author (?)
11	1930	Kunitz	Haddam, Connecticut	W. Kunitz
12	1895	Emerson	Warwick, Massachusetts	E. A. Schneider
13	1914	Eskola	Träskböle, Finland	Pentti Eskola
14	1948	Rabbitt	Ruby River, Madison Co., Montana	Forest Gonyer
15	1920	Shannon	Chesterfield, Massachusetts	E. V. Shannon
16	1914	Eskola	Träskböle, Finland	Pentti Eskola
17	1948	Rabbitt	Cherry Creek Area, Madison Co., Montana	Forest Gonyer
18	1930	Kunitz	Bamble, Norway	W. Kunitz
19	1930	Kunitz	Ötztal, Tyrol	W. Kunitz
20	1937	Rama Rao	Bidaloti, Mysore, India	E. R. Tirumalacher
21	1922	La Croix	Mt. Tsilaizina, Madagascar	Raoult
22	1933	Sundius	Trondhjem, Norway	A. Bygdén
23	1922	La Croix	Mt. Tsilaizina, Madagascar	Raoult
24	1930	Kunitz	jernerud, Norway	W. Kunitz
25	1936	Serdiuchenko	alaya Laba River, North Caucasus, U.S.S.R.	G. Maksimovich
26	1930	Johansson	alun, Sweden	K. Johansson
27	1917	Ishyul	ongsberg, Norway	Author (?)
28	1898	Pratt	akersville, Mitchell Co., North Carolina	Charles Baskerville
29	1948	Rabbitt	herry Creek Area, Madison Co., Montana	Forest Gonyer
30	1948	Rabbitt	illon Complex, Beaverhead Co., Montana	Forest Gonyer
31	1902	Rosický	öhmisch-Schützendorf, Near Deutsch-Brod, Bohemia	Hynek Němeček
32	1939	Uralsky and Buchn	ochnevsky, Southern Urals, U.S.S.R.	Authors (?)
33	1926	Shannon	amiah, Idaho Co., Idaho	E. V. Shannon
34	1930	Kunitz	iask, U.S.S.R.	W. Kunitz
35	1890	Penfield	ranklin, Macon Co., North Carolina	S. L. Penfield
36	1932	Stappenbeck	Morogoro, Tanganyika Territory, Africa	Author (?)
37	1902	Friedel	St. Germain-l'Hermite, France	G. Friedel
38	1936	Rimann	Paakila, Finland	G. Grosser
39	1936	Rimann	Paakila, Finland	G. Grosser
40	1913	D'Achiardi	St. Piero in Campo, Island of Elba	Author (?)
41	1930	Kunitz	Edwards, St. Lawrence Co., New York	W. Kunitz
42	1936	Haapala	Paakkilanniemi, Finland	R. Kalajoki
43	1908	Allen and Clement	Edwards, St. Lawrence Co., New York	E. T. Allen and J. K. Clement
44	1936	Haapala	Tiillikainen, Finland	E. Savolainen
45	1943	Bugge	Vormlitjern, Sondeled, Norway	M. Kluever
46	1939	Uralsky and Buch	Mramorsky, Middle Urals, U.S.S.R.	Authors (?)

The analyses will be discussed under headings to correspond to those of the tables:

1. Selected modern analyses, 1890–1946
2. Selected older analyses prior to 1890
3. Anthophyllite asbestos from Merrill (1895)
4. Poor and incomplete analyses
5. Analyses of doubtful and discredited varieties

Selected Modern Analyses, 1890–1946

There are 46 analyses in this category. Criteria for their inclusion are somewhat arbitrary:

1. The analysis must bear a date 1890 or later. Penfield's careful work on the anthophyllite of Franklin County, North Carolina, was published in 1890.
2. The summation of the analysis mut be 100.00%±0.5%. This standard was set by Hillebrand and Washington on good grounds. Such a summation, of course, does not in itself assure the accuracy of the analysis.
3. In the calculation of the formula, on the basis of 24 (O, OH, F) and 8 (Si, Al), the summation of (Ca, Na, K, Fe″, Fe‴, Mn, Ti, Al) must be 7±0.5. This figure will be called X. Considering all the errors involved, good anthophyllite analyses which can be checked independently will produce an X close to 7 and or the figure falls outside the indicated limits there must be serious error in the analysis or the material is impure, or both.
4. Although fulfilling the conditions above, the analysis must withstand general inspection, admittedly largely subjective. For instance, some constituent such as SiO_2 or MgO might fall far outside the limits shown by the analyses as a group and no convincing evidence be presented to establish the material as anthophyllite on optical or other grounds. An example of this is number 88. It was made in 1896, fulfilling condition 1. The analysis totals 99.32%, not quite meeting condition 2. X equals 7.5 which meets condition 3. MgO equals 7.32%, much too low for any ordinary anthophyllite, and Na_2O equals 3.21%, which is much too high. No good optical data is presented, so the analysis is listed in table 6 as a doubtful variety.

However, certain liberties have been taken with these specifications. I have included two analyses by Shannon (1920 and 1925), numbers 15 and 33, the first of which totals 99.32% and the second 100.92%. But X in the first is 7.39 and in the second 6.95. Furthermore, they are accompanied by optical and other data and the errors in the analysis can not be too serious.

Table 2 consists of part A, the chemical weights per cent; part B, the calculated formulas; and also columns for author, date, locality, and analyst. Part A also contains a column showing the total weights per cent of $FeO+Fe_2O_3+TiO_2+MnO$. Column A ($MgO+CaO+Na_2O+K_2O$), column B ($FeO+Fe_2O_3+TiO_2+MnO$), and column C (Al_2O_3) show the weights per cent of these combinations of oxides, their combined total being 100%. These figures are used to plot the chemical field of anthophyllite on a triangular diagram (fig. 2).

TABLE 3. SELECTED OLDER ANALYSES OF ANTHOPHYLLITE PRIOR TO 1890

A. Chemical weight per cent

No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	F	H_2O-	H_2O+	Total
47	42.86	—	16.52	—	18.82	—	15.51	1.90	—	—	—	—	4.50	100.11
48	43.58	—	17.07	—	15.96	—	18.30	.75	—	—	—	—	3.92	99.58
49	46.74	—	13.70	—	28.09	—	8.76	.77	—	—	—	—	1.90	99.96
50	51.80	—	12.40	—	3.67	—	27.60	—	—— 1.44	——	—	—	3.00	99.91
51	56.88	—	2.45	—	9.65	—	28.50	—	.21	—	—	—	2.28	100.14
52	59.23	—	.19	—	8.27	—	31.02	—	—	—	—	—	1.31	100.02

51. NiO = .17

B. Number of atoms, based on the general amphibole formula (O+OH+F equals 24) where X equals $Ca+Na+K+Mg+Fe''+Fe'''+Mn+Ti+Al$ and Y equals $Si+Al$

No.	X	Y	O	(OH, F)
47	6.50	8.00	19.79	4.21
48	7.23	8.00	20.16	3.84
49	6.90	8.00	22.13	1.87
50	7.00	8.00	22.16	1.84
51	7.05	8.00	21.91	2.09
52	7.27	8.00	22.81	1.19

No.	Date	Author	Locality	Analyst
47	1861	Des Cloizeaux	Gèdres, Pyrenees Mountains, France	F. Pisani
48	1862	Des Cloizeaux	Gèdres, Pyrenees, Mountains, France	F. Pisani
49	1868	Des Cloizeaux	United States	G. Lechartier
50	1877	Pisani	Bamble, Norway	F. Pisani
51	1882	Genth	Castle Rock, Delaware County, Pennsylvania	F. A. Genth
52	1842	Rose	Tschussowaja Springs, Ural Mts., U.S.S.R.	G. Rose

TABLE 4. ANALYSES OF SOME ANTHOPHYLLITE ASBESTOS FROM MERRILL (1895)

	Chemical weight per cent													
No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	F	H_2O-	H_2O+	Total
53	54.56	—	1.47	—	12.39	—	25.28	1.86	—	—	—	—	2.95	98.51
54	54.79	—	—— 13.65 ——		—	—	28.52	—	—	—	—	—	2.55	99.51
55	55.92	—	3.69	—	11.00	—	26.32	.60	—	—	—	—	2.40	99.94
56	56.21	—	2.78	—	8.58	tr	28.95	.82	—	—	—	—	2.23	99.57
57	56.52	—	3.57	—	10.08	—	27.13	tr	—	—	—	—	2.96	100.26
58	56.72	—	1.54	—	10.76	tr	27.46	.10	—	—	—	—	2.88	99.49
59	57.00	—	—— 10.32 ——		—	—	29.98	tr	—	—	—	—	2.29	99.59
60	57.31	—	1.57	—	7.06	—	30.24	—	—	—	—	—	2.73	98.91
61	57.73	—	.72	—	8.61	—	28.77	.08	.57	.14	—	—	2.52	99.14
62	59.00	—	.91	—	6.09	—	29.90	.45	.68	.43	—	—	2.35	99.81

No.	U.S.N.M. No.	Locality	Analyst
53	62090	Carbon County, Wyoming	G. P. Merrill
54	44232	Franklin County, North Carolina	G. P. Merrill
55	—	Tallapoosa County(?), Alabama	G. P. Merrill
56	—	Lenoir, Caldwell County, North Carolina	G. P. Merrill
57	56351	Rabun County, Georgia	G. P. Merrill
58	62604	Alberton, Maryland	G. P. Merrill
59	62748	Warrenton, Warrenton County, North Carolina	G. P. Merrill
60	67001	San Diego, California	G. P. Merrill
61	60842	Nacoochee, Georgia	R. L. Packard
62	50876	Mitchell County, North Carolina	G. P. Merrill

TABLE 5. POOR AND INCOMPLETE ANALYSES OF ANTHOPHYLLITE

A. Chemical weight per cent

No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	F	H_2O-	H_2O+	Total
62a	38.81	—	9.31	—	45.83	—	4.13	.67	—	—	—	—	2.30	101.05
63	41.59	.97	12.81	5.90	14.81	tr	15.13	3.55	.43	.12	2.34	.86	1.68	100.35
64	43.92	—	11.34	—	16.81	1.47	19.14	3.02	—	—	—	—	1.68	97.38
65	50.37	—	10.82	—	15.89	—	19.75	.84	1.59	—	—	—	—	99.26
66	50.80	—	3.60	3.70	6.80	—	26.10	1.20	.20	—	—	—	5.80	98.20
67	51.74	—	8.55	—	20.35	.41	16.45	1.79	—	—	—	—	—	99.29
68	51.88	—	1.01	—	6.21	—	41.02	—	—	—	—	—	.81	100.93
69	52.05	—	9.46	—	20.72	.26	17.24	1.35	—	—	—	—	—	101.08
70	54.48	—	4.68	—	8.16	.32	29.80	.32	—	—	—	None	1.22	98.98
71	55.12	—	.55	—	8.20	.33	31.18	.75	1.55	1.01	—	—	2.21	100.90
72	56.00	—	3.00	—	13.00	4.00	23.00	2.00	—	—	—	—	—	101.00
73	56.00	—	13.30	—	6.00	3.00	14.00	3.33	—	—	—	—	1.43	97.06
74	56.16	—	2.65	—	14.13	.91	23.19	1.51	—	—	—	—	2.38	100.93
74a	56.34	—	2.33	—	9.76	2.05	23.99	.80	.60		—	1.13	1.64	98.04
75	56.74	—	—	—	13.94	2.38	24.35	—	—	—	—	—	1.67	99.08
76	56.86	—	4.50	—	8.13	.87	25.87	1.09	—	—	—	—	3.36	100.68
77	57.12	—	tr	—	13.52	—	25.92	1.32	—	—	—	—	1.36	99.24
78	57.39	—	2.04	.42	6.53	—	29.08	.69	—	—	—	—	2.56	98.71
79	57.90	—	13.55	—	1.90	—	19.40	.87	4.50		—	—	2.86	100.98
79a	58.02	—	—	1.28	—	2.88	27.99	5.04	—	.89	—	—	3.13	99.23
80	58.19	—	.18	—	7.93	—	30.79	—	—	—	—	—	1.86	98.95
81	58.48	—	—	—	9.22	.88	31.38	.04	—	—	—	—	—	100.00
82	59.25	—	2.45	—	6.49	1.05	28.16	1.57	—	—	—	—	—	98.97

63. Average of 2 analyses; deduct .93 for $O=F_2$; $P_2O_5=.16$

B. Number of atoms, based on the general amphibole formula (O+OH+F equals 24) where X equals $Ca+Na+K+Mg+Fe''+Fe'''+Mn+Ti+Al$ and Y equals $Si+Al$

No.	X	Y	O	(OH, F)	No.	Date	Author	Locality	Analyst
62a	7.36	8.00	21.51	2.49	62a	1836	Dufrénoy	Gèdres, Pyrenees Mountains, France	A. Dufrénoy
63	8.01	8.00	21.25	2.75	63	1915	Pawlica	The Tatra, Czechoslovakia	W. Pawlica
64	7.84	8.00	22.37	1.63	64	1882	Sjögren	Snarum, Norway	G. W. Peterson
65	7.98	8.00	24.00	—	65	1905	Böggild	Avisisarlik, Greenland	C. Christensen
66	6.69	7.46	19.02	4.98	66	1888	Teall	The Lizard, Cornwall	X. Player
67	7.60	8.00	24.00	—	67	1878	Wiik	Stansvik, Finland	O. Rosenius
68	9.15	7.27	23.26	.74	68	1894	Doelter	Schneeberg, Germany	J. Ippen
69	7.44	8.00	24.00	—	69	1878	Wiik	Stansvik, Finland	K. Stadius
70	7.41	8.00	22.89	1.11	70	1928	Ross and others	Webster, North Carolina	Forest Gonyer
71	7.79	7.38	22.08	1.92	71	1873	Leeds	Delaware County, Pennsylvania	A. R. Leeds
72	7.26	8.49	24.00	—	72	1862	Des Cloizeaux	Kongsberg, Norway	F. Pisani
73	6.44	8.00	22.52	1.48	73	1831	Vopelius	Kongsberg, Norway	L. Gmelin
74	7.47	8.00	21.67	2.33	74	1809	John	Kongsberg, Norway	J. Fr. John
74a	6.47	8.00	22.50	1.50	74a	1914	Schirmeisen	Podoli, Near Bobrau, Moravia	Matthia Krebs
75	7.10	8.05	22.43	1.57	75	1831	Vopelius	Kongsberg, Norway	L. Vopelius
76	6.58	8.00	21.03	2.97	76	1879	Heddle	Mainland, Shetland Islands	F. Heddle
77	7.25	8.05	22.73	1.27	77	1836	Thomson	United States	T. Thomson
78	6.88	8.00	21.69	2.31	78	1874	Brezina	Hermannschlag, Moravia	E. Ludwig
79	6.61	8.00	21.52	2.48	79	1877	Pisani	Snarum, Norway	F. Pisani
79a	6.90	7.81	21.21	2.79	79a	1896	Cesàro	Edwards, St. Lawrence Co., New York	Renard
80	7.21	7.97	22.31	1.69	80	1843	Rose	Tschussowaja Springs, Ural Mts., U.S.S.R.	G. Rose
81	7.72	8.14	24.00	—	81	1835	Lappe	Koruk, Greenland	M. Lappe
82	7.30	8.21	24.00	—	82	1873	Leeds	Lafayette, Pennsylvania	A. R. Leeds

TABLE 6. DOUBTFUL AND DISCREDITED VARIETIES OF ANTHOPHYLLITE

A. Chemical weight per cent

No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	F	H_2O-	H_2O+	Total
83	42.98	—	2.14	1.50	37.82	—	5.91	1.50	—	—	—	—	5.23	97.08
84	45.87	tr	2.34	6.32	29.34	10.66	1.37	2.31	—	—	—	.30	1.86	100.37
85	46.18	—	21.78	.44	2.77	—	25.05	—	2.30	—	—	—	1.37	99.89
86	47.04	tr	7.02	2.43	26.10	.15	4.96	10.84	tr	tr	—	.45	1.05	100.19
87	47.35	tr	4.20	3.34	36.60	.28	5.80	.77	tr	tr	—	.35	1.25	100.03
88	47.40	—	13.68	—	23.38	2.36	7.32	—	3.20	tr	—	—	1.97	99.32
89	52.44	—	2.62	—	5.71	—	35.83	.43	—	—	—	—	2.74	99.77
90	53.69	—	1.65	.32	5.94	16.10	20.50	1.25	—	—	—	.02	.70	100.17
91	57.12	—	—	—	6.36	—	29.44	—	—	—	—	—	5.74	99.14
92	57.70	None	2.00	tr	5.32	tr	21.12	5.10	7.40	None	None	.30	1.80	100.74
93	62.66	—	13.33	—	12.00	3.25	4.00	3.33	—	—	—	—	1.43	100.00

86. P_2O_5=tr; S=.05; SO_4=.00; CO_2=.10

87. P_2O_5=.04; S=.05; SO_4=.00; CO_2=tr.

B. Number of atoms, based on the general amphibole formula (O+OH+F equals 24) where X equals Ca+Na+K+Mg+Fe″+Fe‴+Mn+Ti+Al and Y equals Si+Al

No.	X	Y	O	(OH, F)	No.	Date	Author	Locality	Analyst
83	—	—	—	—	83	1931	Winchell	Mesabi Range, Minnesota	C. R. Wise
84	6.90	7.95	21.98	2.02	84	1932	Orlov	Jacobemi, Bukovina	Author(?)
85	7.76	8.00	22.78	1.22	85	1889	Ussing	Fiskernäs, Greenland	Author(?)
86	7.30	8.00	22.91	1.09	86	1928	Peacock	Kalkfontein, Cape Province, Africa	W. H. & F. Herdsman
87	7.19	8.00	22.68	1.32	87	1928	Peacock	Penge, Transvaal, Africa	W. H. & F. Herdsman
88	7.24	8.00	22.05	1.95	88	1896	Weibull	Dalekarlien, Norway	J. Petrén
89	7.90	7.50	21.54	2.46	89	1932	Wiesander	Tannwaldgraben, Austria	Author(?)
90	7.64	8.00	23.33	.67	90	1927	Slavik	Chaveltice, Bohemia	V. Veselý
91	6.47	7.59	19.24	4.76	91	1895	Merrill	Salls Mountain, Georgia	R. L. Packard
92	8.00	8.00	22.36	1.64	92	1930	Laudermilk and Woodford	Coffee Creek, Trinity County, California	J. D. Laudermilk
93	5.14	8.55	22.71	1.29	93	1806	John	Kongsberg, Norway	J. Fr. John

Part B shows the number of atoms in the formulas, calculated on the basis of 8 (Si, Al) and 24 (O, OH, F) which is one-fourth the content of the unit cell. It has been suggested by Berman (1937), among others, based on the examination of hundreds of amphibole formulas, that a maximum of 2 silicon atoms can be replaced by aluminum. Where such a replacement occurs an adjustment of valence must take place by the replacement of Mg or Fe'' by ferric iron or by other means. If such a replacement by Al occurred and if the anthophyllite series were a completely isomorphous one from the magnesium to the iron end, then the "end members" with their weights per cent of the constituent oxides would be:

1. $H_2Mg_7Si_8O_{24}$
$MgO = 35.99\%$
$SiO_2 = 61.70\%$
$H_2O = 2.31\%$

2. $H_2Fe_7Si_8O_{24}$
$FeO = 50.25\%$
$SiO_2 = 47.96\%$
$H_2O = 1.79\%$

3. $H_2Mg_5Al_2Si_6Al_2O_{24}$
$Al_2O_3 = 26.08\%$
$MgO = 25.58\%$
$SiO_2 = 46.04\%$
$H_2O = 2.30\%$

4. $H_2Fe_5Al_2Si_6Al_2O_{24}$
$Al_2O_3 = 21.66\%$
$FeO = 38.17\%$
$SiO_2 = 38.25\%$
$H_2O = 1.92\%$

and the possible range in the oxides would then be:

SiO_2	38.25–61.70%
H_2O	1.79– 2.31%
FeO	up to 50.25%
MgO	up to 35.99%
Al_2O_3	up to 25.58%

This is based on ideal considerations. In the natural material small amounts of Ca, Na, K, Ti, and Mn are nearly always present in the crystal structure. It would be expected that Na and K would be less common, and Ca, Ti, and Mn more common in replacing Mg and Fe; the analyses show this to be true.

Part B of table 2 also contains a column showing the ratio of Al replacing Si to Al plus Fe''' replacing Mg, Fe'', etc. Ideally, this ratio should be 1 and where it departs widely from that figure some other adjustment of valence may have occurred or the analysis may be wrong (or the material impure). These questions could be considered fruitfully only if there were a thousand or more analyses with which to work.

Finally, part B also has a column showing the atomic per cent of $Fe'''+Fe''+Ti+Mn$ where these atoms and $Ca+Na+K+Mg+Al$ equal 100%. These figures are useful in considering the degree of isomorphism in the series.

In all of these calculations the figures are carried to the second decimal place; this is probably not justified by the accuracy of the analyses. The ordinary routine mineral analysis is not so accurate as the figures presented would indicate. Rarely, in the case of the more important oxides, as SiO_2, does the second decimal place mean anything; the mineralogist and petrographer would be happy to know that the figures were correct to a few figures in the first decimal place.

In the discussion that follows, the variation of the different oxides is considered and this will give a rounded picture of the chemical side of the series.

SiO_2.—Silica ranges from 42.08% to 60.13%. This nearly covers the theoretical limits of 38.25–61.70%. As the table is arranged in order of increasing silica content it is easy to see that there are no significant gaps in this range. Naturally, with increasing iron and aluminum, silica decreases, the greatest decrease coinciding with increase in alumina.

In the calculated formulas, the number of atoms of silicon ranges from 6.07 (no. 4) to 8.00 for number 44 and 8.05 for number 46. Number 4 represents almost the theoretical maximum replacement of silicon by aluminum. The other two are examples of no replacement and are typical of those anthophyllites nearly or quite aluminum-free.

In most of the examples there is enough silicon and aluminum to satisfy the theoretical maximum of 8 atoms. Some, notably in the aluminum-poor, magnesium-rich range, show a deficiency of either one of these two elements or both, the worst being number 25, where the total is 7.65, followed by number 33, total 7.66, and number 39, total 7.73.

TiO_2.—Titania is present in small amount in many, if not all anthophyllites, notably in the high-aluminum, high-iron ones. It should always be looked for but of the 46 analyses it was determined in only 24. Apparently where alumina is about 10% or more TiO_2 ranges from 0.41% to 1.11%. As alumina decreases the titania falls off sharply to a range from traces to 0.06%. Titanium thus seems to go with either aluminum or iron or both.

CaO, Na_2O, *and* K_2O.—Calcium is nearly always determined and ranges up to 3.45% CaO. There is some possibility that this represents impurity. The usual amount is about 0.5% and this seems to be definitely in the crystal structure.

Soda is not always determined but where it is the range is up to 1.34%, with the average being about 0.5%. In four analyses, only total alkali is given, a practice to be condemned. There is no doubt that some soda enters the crystal structure.

Potassium is usually present in negligible amounts or is completely absent. It should always be determined for the sake of completeness but where more than about 0.5% is present impurity should be suspected.

Potassium, on account of its large ionic volume as compared to magnesium and iron, would not be expected to enter the anthophyllite structure to any large extent. The figures confirm this idea.

Al_2O_3.—Alumina is more important in the anthophyllite series than has been realized. The series is usually regarded as a magnesium-iron one but it is clear that it is a ternary system. Of the 46 analyses, 14 show more than 10% Al_2O_3 and 20 show more than 5%. The amount ranges up to 23.79% (no. 4). Despite this, there are such statements as Winchell's (1931) to the effect that "the anthophyllite series differs from all other amphiboles, not only in simplicity of composition, due to the absence of Ca, Al, and Na atoms . . . ." Sundius (1933) does not stress the importance of aluminum although he does plot the composition of the Ca-poor amphiboles on a three-component diagram, one component being $Al_2O_3+Fe_2O_3$. Tilley (1939) uses a similar diagram in which Al_2O_3 is one of the components.

The substitution of Al atoms for Si atoms and the accompanying substitution of Al (and Fe‴) for Mg and Fe″ is reflected in the formulas. The ratio of Al in the first case to Al+Fe‴ in the second, which should be 1, rarely is so perfect. Analysis number 4, showing almost the maximum replacement, has a ratio of 1 but many others diverge widely from this (nos. 6, 7, 11, 12, 17, 18, and others).

In general, high-alumina means high-iron but there are many exceptions. The peak of alumina content seems to come about midway in the series; it is noteworthy that aluminum is a minor element in the cummingtonite series which is high in iron.

FeO and Fe_2O_3.—Ferrous iron ranges up to 26.53%. In reality the series is not filled out to the magnesium end as numbers 41 and 43, which contain practically no FeO, do have 2.53% and 2.77% MnO plus 0.52% and 0.29% Fe_2O_3 respectively. These, from Edwards, New York, are the purest anthophyllites known.

At the iron end it is apparent that the series is not completely isomorphous. A pure iron end member would contain 50.25% FeO. One with the maximum amount of alumina would contain 38.17% FeO (with 21.66% Al_2O_3). Number 2 shows the highest iron content (26.53%) and $FeO+Fe_2O_3+MnO$ equals 30.29% (with Al_2O_3 10.88%). It is seen that the series is one of limited miscibility. Evidence will be presented to show that the so-called anthophyllites with an FeO content higher than that of number 2 are monoclinic by *x*-ray examination. In the formulas the $Mg/Fe''+Fe'''+Mn$ ratio of number 2 is 2.63/3.80.

Ferric iron is present in limited amount in many anthophyllites. It is doubtful if all the Fe_2O_3 reported by the chemist is always a true reflection of the original amount. The ease with which FeO is oxidized in the preparation of the sample makes any figure representing Fe_2O_3 subject to suspicion. Only by exercising extreme care can the chemist make an accurate determination of this oxide. For this reason, such figures as 0.20% (no. 4) and 0.33% (no. 12) are not important. However, we must accept 7.03% (no. 21) and 8.28% (no. 25) as representing a real presence of Fe''' in the structure. In principle we might expect high Fe_2O_3 to go with high Al_2O_3 but this is not clearly apparent. Ferric iron seems to follow ferrous iron as much as aluminum, a condition which may reflect some oxidation.

MnO.—Manganese is not important in the anthophyllite series. Four analyses (nos. 11, 18, 41, 43) show more than 1.00% MnO, the highest being 2.77%. The rest average about 0.25%. Some high-Mn anthophyllites (up to 16.10% MnO) have been described but it will be shown in the section on *x*-ray study that these are cummingtonites. The cummingtonite series contains many varieties high in manganese. It may be that Mn, with an ionic volume of 3.14, more easily substitutes for Fe'', with an ionic volume of 2.39, than for Mg with an ionic volume of 1.97.

MgO.—Magnesia ranges from 11.48% (no. 2) to 31.53% (no. 40). In the formulas, number 40 shows the highest Mg content (6.38) but $X=7.20$ and $Fe''=0.63$. Number 41, on the other hand, has a Mg content of 6.13 and $Mg+Ca+Na$ equal 6.67 where X is 7.00. There is no Fe'', and $Fe'''+Mn$ equal 0.33. This purest anthophyllite thus has a ratio of $Mg+Ca+Na/Fe'''+Mn$ of 6.67/0.33, fairly close to an end member.

Fluorine.—No amphibole analysis is complete without a fluorine determination, but there are only twelve such determinations, including the seven made on the Montana specimens, in the list. Six of the Montana analyses show no fluorine; the other (no. 1) shows 0.31%. This seems to be an average amount for those that have any fluorine but it is to be regretted that more determinations have not been made. It is true that a good fluorine determination on an amphibole is not easy for any chemist, but the analysis should always be required.

Water.—Up to 1930 it was generally believed that anthophyllite was anhydrous despite the fact that Schaller (1916) had shown that OH was part of the tremolite formula. Penfield (1890) also realized that the water always appearing in an amphibole analysis was water of constitution and he devised the Penfield method for the determination of such water in amphiboles and other silicates (Penfield 1894). This method, with some modifications of apparatus, is the one in general use today. In the period before 1890, water of constitution (H_2O+) was determined usually by ignition; the material was heated in a crucible to red heat and the loss in weight computed as "loss on ignition" equated to H_2O+. H_2O- was computed as adsorbed water and was driven off by heating the sample to 105°–110° C.

Determination of water by ignition is subject to serious error. Any ferrous iron present will oxidize to ferric iron and a gain in weight might result. Hence the method should not be used today.

The Penfield method was used in the determination of H_2O in the seven Montana specimens. In six of the seven specimens what was regarded as normal amounts of water were secured at the temperature used in the method, about 1000° C. for five minutes. The seventh specimen (no. 30) showed only 0.28% H_2O by this procedure. This was so much lower than the water content of any other anthophyllite that the determination was repeated and the heating was continued for 15 minutes. This resulted in 1.43% H_2O which indicated that something might be wrong with the method. The material was subjected to differential thermal analysis (described further on in this section) and it was seen that water was not fully driven off at a temperature of 1050° C. maintained for 15 minutes.

Mr. Forest Gonyer then suggested that a method be used based on the use of the tubulated crucible described by Gooch. In this method, the material is fused with anhydrous sodium carbonate in a type of tubulated crucible and water can be collected in any one of a number of ways. If done carefully, this procedure assures that all the water is driven off; the collection of the water involves merely the technical skill of the chemist. In this method, 2.06% H_2O was secured from specimen number 30, which was calculated to 1.88 (OH) in the formula. It is thought that this represents the best possible determination of water.

This tends to confirm the belief held by some chemists and mineralogists that all determinations of water in amphiboles involving the Penfield or similar methods may be and probably are wrong. It has been known for a long time that water in the amphiboles cannot easily be driven off, even at 1000° C. or 1100° C. There have been, of course, many studies made of this problem together with the parallel one of whether or not the loss of water was accompanied by atmospheric oxidation. Barnes (1930) presented a summary of this work and in a study of his own, in heating hornblende to 800° C., concluded in part that

> In dehydration, hydrogen and not water (except water that is not a constituent part of the space lattice) is given off, and the oxygen remains in the mineral, either oxidizing ferrous to ferric iron or, when ferrous iron is not present, remaining because of its size.

There is no general agreement on the behavior of water in the amphiboles during heating nor at what temperatures the different fractions of water are given off. For instance, Belyankin and Donskaya (1939) in a specimen of actinolite containing 3.73% H_2O, found that on heating, the loss of total water was 1.68% at 400° C., 2.42% at 800° C., and 3.64%, or nearly all, at 950° C. Here, of course, it is not certain that the original analysis secured all of the water.

In trying to solve some of these questions a differential thermal analysis was made on three of the Montana specimens (nos. 14, 29, 30) and a high-iron cummingtonite from the same area as number 17. The runs were made by Dr. Carl Beck who has made a differential thermal analysis study of carbonates for a Ph.D. thesis (May 1946) in the Department of Mineralogy at Harvard University. The resulting curves are reproduced in figure 1 together with a curve for gibbsite from Dr. Beck's thesis. These curves show exothermic and endothermic reactions occurring in the specimen during heating. The reactions are reproduced as deviations of the trace of the zero line, endothermic below and exothermic above. The area of the deviation is proportional to the energy involved. The curves start at 50° C. and proceed up to 1050° C. (the safe limit of the apparatus) at a steady rate of 50° C. for about every 4 minutes.

The curves are disappointing in that no clear interpretation is possible and no markedly sharp breaks are evident. The difficulty in interpretation is due to the simultaneous loss of water and oxidation of ferrous iron. The first is endothermic, the second exothermic, and the resultant trace may be above or below the zero line. The curves do show that there is a gradual loss of water from 150° C. to about 500° C. and that probably another loss begins at about 750°–850° C. Number 14 shows a rather sharp shallow break from 1000° to 1025° C. and the same break occurs in number 29. This is probably a sudden loss of water; all of the specimens show a vague continuing loss at 1050° C. at the conclusion of the runs and it can be said that in none has all the water been driven off. In contrast to these curves the gibbsite shows a clear deep break at 250° C., reaching a maximum at about 350° C. The trace returns to the zero line at 425° C. and continues unswervingly on this line to the end of the run at 1000° C. This break shows the loss of water and the curve is most satisfactory.

This study settled nothing but tended to confirm the idea that water is not thoroughly driven off in the Penfield method. Time did not permit the redetermination of the water in the other six Montana specimens and it must be admitted that in them the figures for H_2O are probably somewhat low.

Chemical Field.—The 46 analyses are plotted on a triangular diagram as shown in figure 2. The three components are weights per cent of ($MgO+CaO+Na_2O+K_2O$), ($FeO+Fe_2O_3+TiO_2+MnO$), and Al_2O_3, the combination of these oxides equalling 100%. The numbers of the Montana specimens are underlined. It is seen that there is a distinct concentra-

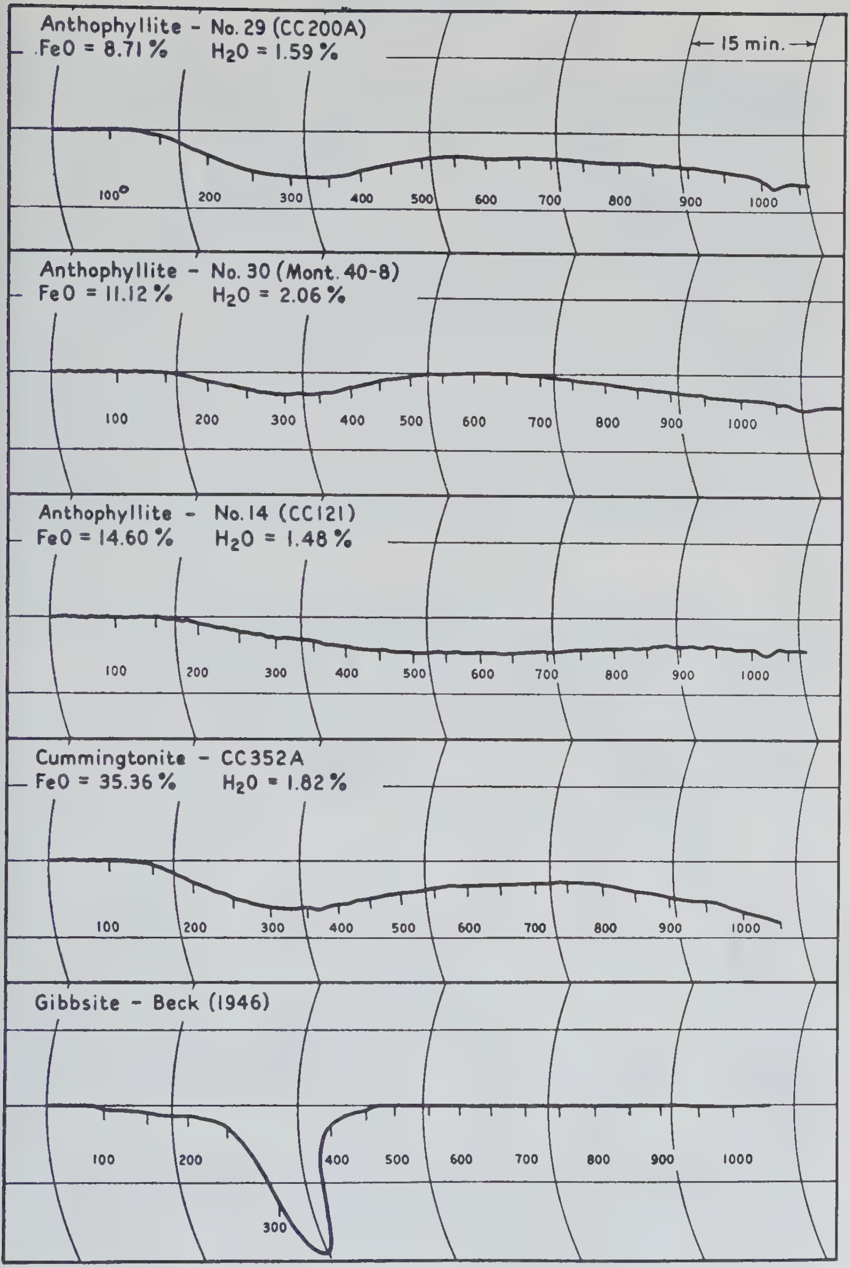

FIG. 1. Differential thermal analysis curves for three anthophyllites and one cummingtonite. These are compared to one for gibbsite which shows clearly a loss of water reaching a peak at about 350° C. Figures running horizontally along the bottom of each curve are degrees C.

tion at the high-magnesia, low-alumina corner of the plot and another approximately in the center. The iron corner, of course, is blank and

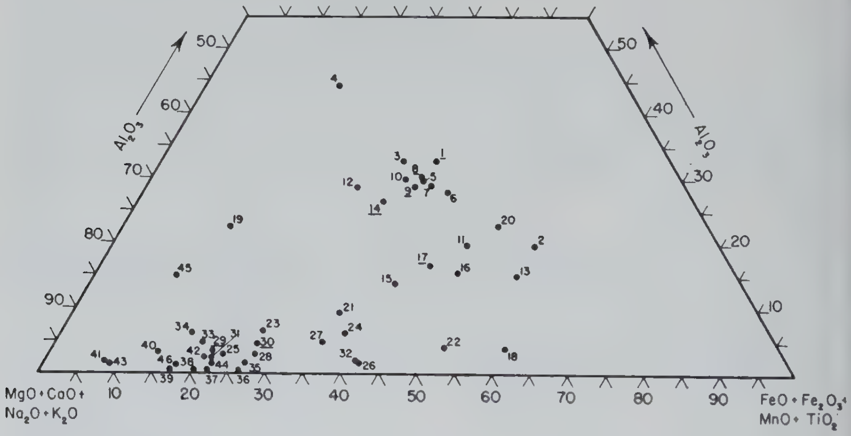

FIG. 2. Composition of 46 anthophyllites whose compositions are shown in table 2. The numbers of the Montana varieties are underlined. The plot is based on the chemical weights per cent of the oxides shown, the sum of these oxides being 100%.

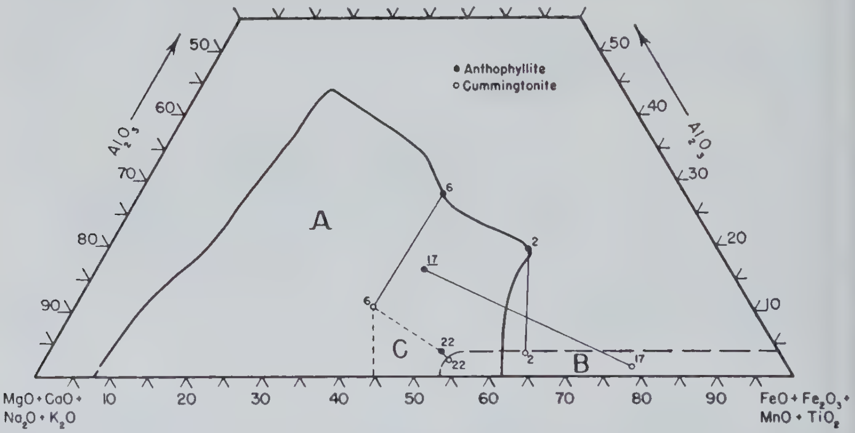

FIG. 3. The chemical fields of anthophyllite and cummingtonite outlined from figure 2. "A" is the anthophyllite field; "B" is the cummingtonite field after Sundius (1933); "C" is a possible extension of "B" to accommodate the cummingtonite of Collins (1942). The four pairs of anthophyllite and cummingtonite whose analyses are given in table 7 are plotted and connected with lines.

there is a blank area centering around 40(FeO), 15(Al_2O_3), and 45(MgO). There are not enough analyses to show if this gap is real or not.

The field outlined by these analyses is shown in figure 3. "A" represents the anthophyllite field, "B" is the cummingtonite field, after Sundius (1933), and "C" is a possible extension of this field which includes a cummingtonite recently described by Collins (1942). Three occurrences of anthophyllite with cummingtonite have been described (nos. 2, 6, 22) and a fourth from Montana (no. 17) is presented here. These are shown in figure 3, the numbered solid dots representing anthophyllites tied to their accompanying cummingtonites shown by similarly numbered circles. It is probable that pair number 22 was in equilibrium but it is apparent, both from the author's description and the plot, that the others were not. The cummingtonite of number 6 is unusual in being high in alumina, and in being rather deep in the anthophyllite field. This may indicate a large overlap in the two fields.

The analyses of the four anthophyllites and their corresponding cummingtonites are shown in table 7.

TABLE 7. ANALYSES OF ANTHOPHYLLITE AND CUMMINGTONITE, EACH PAIR FROM THE SAME ROCK

(A = anthophyllite; C = cummingtonite)

	No. 2 (Eskola 1936)		No. 6 (Collins 1942)		No. 17		No. 22 (Sundius 1933)	
	A	C	A	C	A(CC352C)	C(CC352A)	A	C
SiO_2	43.70	50.70	44.70	49.60	50.36	50.32	53.93	54.28
TiO_2	.55	.31	.57	.26	.43	None	.02	.02
Al_2O_3	10.88	1.72	14.70	8.65	8.06	.86	1.79	1.26
Fe_2O_3	3.52	3.11	1.62	.48	2.18	1.75	1.84	.80
FeO	26.53	26.63	18.96	18.54	18.26	35.36	20.50	21.79
MnO	.24	.19	.21	1.08	None	.02	.25	.26
MgO	11.48	14.36	14.89	16.78	17.57	8.61	18.92	18.64
CaO	.54	.87	.69	.97	.74	.88	.12	.15
Na_2O	1.24	.60	1.34	.79	.70	.13	.15	.14
K_2O	.15	.15	None	None	None	None	.07	tr
H_2O+	1.21	1.46	2.27	2.52	1.69	1.82	2.08	2.16
F	—	—	—	—	None	None	.53	.57
Total	100.14	100.10	100.26	100.30	99.99	99.93	100.20	100.07

No. 6A—H_2O- = .29
No. 6C—H_2O- = .29; P_2O_5 = .34
No. 22A—Deduct .22 for $O = F_2$
No. 22C—Deduct .24 for $O = F_2$

Analysts: No. 2, Tauno Kervinen; No. 6, Geochemical Laboratories; No. 17, Forest Gonyer; No. 22, A. Bygdén.

Selected Older Analyses Prior to 1890

The 6 analyses in this category are shown in table 3. Although they fulfill some of the conditions for "good" analysis they have not been used in the preceding discussion since they lack TiO_2, Fe_2O_3, and F determinations and are deficient in other ways. The formulas are not shown in detail but X, Y (Si+Al), O, and (OH, F) are included under heading B.

Anthophyllite Asbestos from Merrill (1895)

Table 4 contains 10 typical anthophyllite asbestos analyses presented in a study of asbestos and asbestiform minerals by Merrill (1895). They have been grouped in this way to show clearly the composition of such asbestos. As most of them are not complete analyses the formulas have not been calculated. They are complete enough, however, to show that they are not uncommonly high in soda although it is often said that amphibole asbestos is characterized by high soda content. Generally, these specimens are low in iron and aluminum, which may be a reflection of their environment. It cannot be said that all amphibole asbestos is low in iron as one of the amosites of Peacock (no. 87) has 39.94% $FeO+Fe_2O_3$.

These specimens are also characterized by a high water content, running from 2.29% to 2.95%. This is to be expected as water at the magnesium end of the series should be 2.31% and it decreases with increase of iron and aluminum. However, water determinations in Merrill's samples were made by the ignition method, so the results are not trustworthy.

Poor and Incomplete Analyses

There are 23 analyses under this heading, shown in table 5. In age they range from John's in 1809 to Ross's in 1928. They are included here because in one way or another they fail to meet the criteria established for "selected" analyses. In some of them (nos. 65, 67, 72, 81, and 82) no water determinations were made. In some, such as numbers 69 and 72, the summation is much too high, and in others, such as numbers 80 and 82, it is much too low. In the formulas X is much too high in some (nos. 63, 65, 69) and somewhat low in others (nos. 73, 74*a*). The one of Ross, number 70, is not a poor but an incomplete analysis. The analysis accompanying the original description of gedrite, number 62a, shows a very high FeO content (45.83%), which has not been duplicated in any of the many analyses made on gedrite from Gèdres since that time.

Despite their inadequacies these analyses do add somewhat to our knowledge of the chemical variation in the anthophyllite series.

Analyses of Doubtful and Discredited Varieties

Eleven analyses are listed under this heading in table 6. In the following discussion the reasons for regarding these specimens as doubtful or discredited anthophyllites are examined insofar as their composition is concerned.

Number 83.—This was presented by Winchell (1931) as "Anthophyllite, Mesabi Range, Minn. Incomplete analysis by C. R. Wise." Its high FeO content (37.82%), without any good evidence that it is orthorhombic, indicates that it is probably cummingtonite, or perhaps a mixture of that mineral and anthophyllite. The high H_2O content (5.32%) makes its purity questionable.

Number 84.—This specimen, a high-MnO (10.66%), high-FeO (29.34%) amphibole from Jacobemi, Bukovina, described by Orlov (1932), is probably the cummingtonite variety dannemorite. Evidence to that effect will be given in the section on *x*-ray properties.

Number 85.—The orthorhombic nature of this high-alumina (21.78%) amphibole described by Ussing (1889), from Fiskernäs, Greenland, has never been questioned. However, in a specimen in the Harvard collections (no. 86379) labeled "Anthophyllite and Sapphirine from Fiskernäs, Greenland" the amphibole is monoclinic. In all other respects (optical properties, color, and so forth) it matches the material described by Ussing. The situation is further confused as monoclinic colorless amphibole occurs in the same locality. Ussing was a careful worker and he presented detailed optics for his material, but his identification of this material might be mistaken. Until the Greenland specimen can be reexamined it should be regarded as a doubtful anthophyllite.

Numbers 86 and 87.—These analyses are of two amosites from South Africa described by Peacock (1928). It will be shown by *x*-ray evidence that both are monoclinic. As they are monoclinic, their composition shows that number 86 is probably actinolite (10.84% CaO, 29.34% FeO, 4.96% MgO) and number 87 is probably cummingtonite (36.60% FeO, 5.80% MgO, 0.77% CaO). Both of these specimens are asbestiform and their identification cannot be determined by optical methods.

Number 88.—Reasons have already been given in the section why this specimen from Norway should be considered as doubtful.

Number 89.—The chemical composition of this material from Austria. described by Weisander (1932) is not that of anthophyllite. It shows 35.83% MgO, only 0.16% short of the theoretical maximum but it also contains 5.71% FeO and 2.62% Al_2O_3 when these should be absent. SiO_2 is 52.44% when it should be more than 61% for such a MgO content. The analysis was poor, the material was impure, or the mineral was not anthophyllite.

Number 90.—Slavik's (1927) so-called manganese-rich anthophyllite from Chaveltice, Bohemia, will be shown by *x*-ray study to be monoclinic. This being so, its composition (MnO 16.10%, FeO 5.94%, MgO 20.50%) makes it the high-manganese variety of cummingtonite, dannemorite.

Number 91.—Samples of many of the anthophyllite asbestos specimens described by Merrill (1895) were sent to me by the U. S. National Museum for *x*-ray study. One of them from Salls Mountain, Georgia, number 61357, could not be found. Similar material, number 88286 was sent and was found to be chrysotile. This substitute material has not been analyzed and there is no assurance that it is the same as the original. Until anthophyllite is identified from this locality by *x*-ray study this occurrence must remain doubtful.

Number 92.—Laudermilk and Woodford's "Soda-rich anthophyllite asbestos" from California, described in 1930, will be shown by *x*-ray study to be monoclinic. As it has 5.10% CaO and 7.40% Na_2O, coupled with 21.12% MgO and 5.32% FeO, it can be called a soda tremolite.

Number 93.—This analysis by John (1806), the earliest from the literature, does not fit any probable anthophyllite. It would be futile to speculate as to what is wrong with it.

SPECTROGRAPHIC ANALYSES

No spectrographic analyses of anthophyllite were found in the literature. Some minor metals were determined spectrographically in the seven Montana anthophyllites (nos. 1, 8, 9, 14, 17, 29, 30), in one from Russia (no. 10), in two of Merrill's asbestos varieties (no. 53 from Wyoming and no. 59 from North Carolina), and in the cummingtonite (no. CC352A) occurring in the same rock as no. 17 (see table 7 and fig. 3).

TABLE 8. SPECTROGRAPHIC ANALYSES OF 10 ANTHOPHYLLITES AND ONE CUMMINGTONITE
Analyst, John C. Rabbitt

Anthophyllite	Weights per cent (dashes = <0.001%)												
	Ag	Ba	Co	Cr	Cu	Li	Mo	Ni	Pb	Sn	Sr	V	Zr
1. (CC206F)	.004	—	.003	—	.004	.03	—	.002	—	—	—	.001	—
8. (CC298)	.002	—	.007	.03	.005	.03	—	.01	—	—	—	.04	.001
9. (Mont.40-12)	.002	—	.006	.02	.005	.03	—	.008	—	—	—	.03	.002
10. (Ka10)	.003	—	.004	.01	.006	.04	—	.01	—	—	—	.01	.003
14. (CC121)	.002	—	.005	.003	.005	.03	—	.004	—	—	—	.03	.001
17. (CC352C)	.003	—	.008	.002	.02	.04	—	.006	—	—	—	.05	.001
29. (CC200A)	.002	—	.007	.2	.008	.005	—	.1	—	.002	—	.01	.002
30. (Mont.40-8)	.002	.006	.006	.03	.003	.02	—	.06	—	—	—	.001	.002
53. (USNM 62090)	.002	—	.007	.006	.03	.001	—	.07	—	—	—	—	.003
59. (USNM 62748)	.008	—	.008	.008	.02	.002	—	.06	—	—	.008	—	.001
Cummingtonite													
CC352A	.003	—	.003	.005	.01	.002	.001	.01	.001	.002	.001	.002	.005

Not found (<0.001%): As Au B Be Bi Cb Cd Ce Cs Ga Ge Hg In Ir Os Pd Pt Rh Ru Sb Sm Ta.

The results of the analyses are shown in table 8. Of the 35 metals determined, only 13 occurred in significant quantities (>0.001%) in any of the samples. These are silver, barium, cobalt, chromium, copper, lithium, molybdenum, nickel, lead, tin, strontium, vanadium, and zirconium. None of these occurred in amounts greater than 0.2% (Cr in no. 29).

There does not seem to be any definite variation of these minor metals with any of the major constituents. The cummingtonite specimen has a greater diversity of the minor metals than the anthophyllites but the total weight per cent is much less than that of the anthophyllites except number 1.

There seems to be a greater concentration of nickel and copper in the high-magnesium anthophyllites (nos. 29, 53, 59) and a lower concentration of lithium than in the others. Until spectrographic data is secured on many more specimens the question of the variation of the minor metals in the members of the anthophyllite series must remain a matter for future study.

Optical Properties

Montana Varieties

Indices of Refraction.—The indices of refraction were measured by the Emmons double-variation method. The apparatus used was one devised by Professor Cornelius Hurlbut (1947) of Harvard and it has some modifications of the standard Emmons apparatus. These changes lead to better temperature control and in practice seem to be satisfactory.

It is generally believed that measurements by the Emmons method are precise to about ±0.0002 and with extreme care to ±0.0001. It is my belief, however, that in routine operation the precision is never better than ±0.0005. When the difficulty of controlling the temperature to much better than ±0.5° is considered, together with the difficulty in maintaining the adjustment of the refractometer, it is probable that ±0.0005 is about the best that can be done. For most purposes in mineralogy indices to ±0.001 are more than adequate. For example, most cleavage flakes of anthophyllite vary slightly in index from end to end so that nZ can vary ±0.0005 or more on the same small flake. This is also true of the other indices. The chemical analysis is made on a countless number of these small flakes and represents an average composition. The indices are measured on one or two flakes but the range in all those used for chemical analysis might be ±0.001. If this be so, then comparing the chemical and optical properties of such material on the basis of index measurements to ±0.0005 or better is a waste of time. This is true for complex minerals such as the amphiboles. There may be some justification for more precise work on minerals such as quartz in which any one grain in a large collection will have about the same composition and optical properties as the next. Even here the accuracy of the chemical analysis does not warrant such close work.

The indices as shown in table 9 are given to the fourth decimal place but from the preceding discussion it must be remembered that they are no better than ±0.0005 and possibly ±0.001. The indices *n*X, *n*Y, and *n*Z are given for wave lengths of light corresponding to the F-line (4861.3 Å), the D-line (5892.9 Å), and the C-line (6562.8 Å). These figures lead to the dispersion of the indices, F–C. For *n*Z this ranges from 0.0133 in number 30 to 0.0220 in number 9. For *n*Y it ranges from 0.0135 in number 29 to 0.0272 in number 9. For *n*X it ranges from 0.0178 in number 29 to 0.0297 in number 9. The extreme range, *n*Z to *n*X, for all of them is 0.0133 to 0.0297.

Dispersion of the indices is a property which has not been measured on many anthophyllites. I can find only two examples, 0.014 (presumably for *n*Z) in numbers 38 and 39 on asbestiform material from Paakila, Finland by Rimann (1936).

It was hoped that this dispersion might be a property which varied significantly with chemical composition, such as iron or aluminum content. Plots made on this assumption are disappointing; the dispersion varies erratically and shows no definite relation to composition. No plot is needed to show that the dispersion is in all varieties greater for *n*X than for *n*Z. More measurements of this property are needed and when a hundred or so are available some significant variation with composition should be revealed.

Birefringence, *n*Z minus *n*X, for the three wave lengths is also shown in table 9. For the F-line it ranges from 0.0094 in number 14 to 0.0165 in number 30. For the D-line it ranges from 0.0131 in number 17 to 0.0248 in number 30. For the C-line it ranges from 0.0150 in number 17 to 0.0280 in number 30. In general, birefringence increases with increasing magnesium.

Optic Sign and 2V.—It has never seemed to me worthwhile to attempt precise measurements of 2V. This property is inherent in the indices and can be calculated from them, or can be secured graphically. When questions of identity arise 2V can be easily estimated in microscopic examination to about ±5°, depending on its size. Whether on the Fedorov stage or by other methods, 2V can be measured only to about ±1° (except with the axial angle apparatus when used on special materials). Nevertheless it is common to see figures for it given to minutes and in some cases to seconds.

TABLE 9. OPTICAL PROPERTIES OF SEVEN MONTANA ANTHOPHYLLITES

A.—Indices of refraction

F = 4861.3 Å D = 5892.9 Å C = 6562.8 Å

					Birefringence Z−X		
	F	D	C	Dispersion F−C	F	D	C
1. (CC206F)							
Z	1.6910	1.6781	1.6726	.0184			
Y	1.6839	1.6670	1.6600	.0239	.0159	.0215	.0249
X	1.6751	1.6566	1.6477	.0274			
8. (CC298)							
Z	1.6821	1.6718	1.6673	.0148			
Y	1.6768	1.6630	1.6570	.0198	.0111	.0165	.0188
X	1.6710	1.6553	1.6485	.0225			
9. (Mont.40-12)							
Z	1.6850	1.6695	1.6630	.0220			
Y	1.6792	1.6603	1.6520	.0272	.0122	.0175	.0199
X	1.6728	1.6520	1.6431	.0297			
14. (CC121)							
Z	1.6725	1.6619	1.6574	.0151			
Y	1.6681	1.6545	1.6488	.0207	.0094	.0143	.0164
X	1.6631	1.6476	1.6410	.0221			
17. (CC352C)							
Z	1.6777	1.6671	1.6630	.0147			
Y	1.6736	1.6595	1.6540	.0196	.0097	.0131	.0150
X	1.6680	1.6540	1.6480	.0200			
29. (CC200A)							
Z	1.6451	1.6354	1.6315	.0136			
Y	1.6365	1.6370	1.6230	.0135	.0146	.0174	.0188
X	1.6305	1.6180	1.6127	.0178			
30. (Mont.40-8)							
Z	1.6505	1.6410	1.6372	.0133			
Y	1.6430	1.6280	1.6205	.0225	.0165	.0248	.0280
X	1.6340	1.6162	1.6092	.0248			

B.—Optic sign, 2V, orientation, and pleochroism

	F	D	C	X	Y	Z
1.	(−) 86°	(+) 87°	(±) 90°	pale tan	pale tan	tan
8.	(−) 88°	(+) 86°	(+) 85°	pale tan	pale tan	tan
9.	(−) 84°	(+) 87°	(+) 84°	pale tan	pale tan	smoke gray
14.	(−) 88°	(+) 87°	(+) 86°	pale tan	pale tan	tan
17.	(−) 84°	(+) 81°	(+) 78°	pale tan	pale tan	tan
29.	(+) 80°	(−) 88°	(−) 84°	colorless	colorless	colorless
30.	(−) 85°	(+) 88°	(+) 79°	colorless	colorless	colorless

Pleochroism in 1, 8, 14, and 17 is weak; in 9 it is moderate.
Absorption is $X = Y < Z$.
Orientation in all varieties: $Z = c$ and $Y = b$.

For the Montana specimens 2V was approximated graphically from the indices and the figures are correct to about ±2°. Table 9 shows that for the D-line all the specimens are optically (+) except number 29, and have 2V's greater than 80°. All change sign for the F-line and all decrease in 2V for the C-line (except no. 1) but retain the same sign as that for the D-line.

Orientation and Pleochroism.—The orientation in these specimens, as in all anthophyllites, is $Z=c$ and $Y=b$. In immersion most fragments will lie on a cleavage face which is usually elongated. It is thus easy to measure nZ in this direction. Across the cleavage flake the index measured will be nX' and to measure true nX it is necessary to turn the grain, not a difficult operation. In any collection of grains some will be found showing an optic-axis interference figure and nY can be measured on such a grain. Here again it may be necessary to roll the grain somewhat to get the true figure.

In five of the specimens, pleochroism is perceptible and in two (nos. 29 and 30) it is not. In only one, number 9, is it anything more than weak. The colors to me seem to be shades of tan but they might also be referred to as clove, clove brown, straw yellow, buff, and so forth. In general pleochroism increases with increasing iron and this seems to be true for all anthophyllites. In all varieties the absorption is $X=Y<Z$.

Varieties from the Literature

Table 10 shows what optical properties are available for those anthophyllites which were discussed under the heading "Selected Modern Analyses, 1890–1946" in the preceding section and whose chemical analyses are shown in table 2. Of these, exclusive of those from Montana, 26 have some optical data out of a total of 39. The completeness of the data ranges all the way from adequate for the thorough work of Penfield (1890) shown in number 35, to a mere notation of the optic sign by Emerson (1895) as in number 12. In only a few others is complete data presented (as in nos. 6 and 20) so that the best that can be done until more is secured is to draw broadly general conclusions from what is available.

Indices of Refraction.—Figure 4 shows nZ plotted against weight per cent of $FeO+Fe_2O_3+TiO_2+MnO$. This combination is valid, as ferrous iron and manganese affect the indices about equally and ferric iron and titanium are usually not present in quantities great enough to distort the results. There are many possible ways of plotting these figures. Winchell prefers to plot the properties against molecular percentages of end members. In the anthophyllite series he uses $H_2Mg_7Si_8O_{24}$—$H_2Fe_7Si_8O_{24}$ (see Winchell 1938). Sundius (1933) used $MgSiO_3$–$Fe(Mn)SiO_3$.

TABLE 10. OPTICAL PROPERTIES OF SOME ANTHOPHYLLITES FROM THE LITERATURE

	nX	nY	nZ	nZ−nX	Sign and 2V	Remarks
2.	1.674	—	1.697	.023	(+) —	
3.	1.651	—	1.672	.021	(+) —	
4.	1.642	1.655	1.661	.019	(−) large	Indices ±0.003
6.	1.652	1.656	1.666	.014	(+) 85°	Positive elongation
7.	1.643	1.653	1.659	.016	—	Positive elongation
10.	1.642	1.648	1.658	.016	(+) 78°	
12.	—	—	—	—	(−) —	
13.	—	1.662	1.676	—	70°–80°	
15.	1.644	—	1.660	.016	—	
16.	—	1.653	1.667	—	70°–80°	
20.	1.656	1.667	1.672	.015	(−) 57°	2V±2°; red<violet
21.	—	—	—	—	(−) —	
22.	1.6454	1.649	1.6605	.015	(+) 59.3°	Birefringence measured
24.	1.629	—	1.652	.021	(−) —	
25.	1.626	1.638	1.651	.025	(+) 87°	Red<violet
26.	1.6329	1.6384	1.6517	.0188	(+) 66°02′	2V measured with optic angle apparatus
33.	1.605	—	1.625	.020	—	
34.	1.608	—	1.631	.023	—	
35.	1.6195	1.6301	1.6404	.0209	(−) 88°46′	As corrected by Bowen; 2V measured with optic angle apparatus
38.	1.605	—	1.626	—	—	nX is nX′; F−C=0.014
39.	1.60	—	1.623	—	—	nX is nX′; F−C=0.014
40.	—	1.64	—	—	(−) 67°	nZ minus nY=0.0065
41.	1.598	—	1.623	.025	—	
43.	—	—	1.62	—	—	
44.	—	—	1.634	—	—	
45.	1.610	1.627	1.630	.020	(−) 69°	2V measured on the Fedorov stage

	Pleochroism and orientation		
	X	Y	Z
3.	greenish yellow	greenish yellow	grayish green
5.	pale yellow	brownish yellow	dove gray
6.	yellow	brownish	smoke gray
13.	pale clove brown	clove brown	dark brown
15.	colorless	colorless	colorless
16.	colorless	colorless	colorless
20.	pale yellow to colorless	same to pale brownish	lilac
25.	colorless	colorless	gray brown

In all of these Z=c, Y=b, the optic plane is parallel to (010), and absorption is X=Y<Z.

Orlov (1932) used the same system. Bowen used molecular per cent of $FeSiO_3$ in 1920 and the Winchell system in 1933 which was also used by Kunitz (1930). These are enough examples to show that this concept of molecular end members is well entrenched and yet it is founded on false premises. No such end members in the amphiboles are known in nature. No such mixing on a molecular basis occurs. However convenient it may be to plot the different properties in that way it must be admitted that it engenders and perpetuates a false notion of the variations in a mineral series. Collins (1942) phrases the objections well:

> Winchell . . . Sundius, and Alling plot the optical properties against percentages of "minals," which Alling claims gives a clearer picture than do the complex mineral compounds. In nature no pure "minals" exist. They are hypothetical compounds and the suitability of plotting optical properties against them is doubtful. The "minal" method shows a definite trend, increase of iron content causing increase in refractive indices, but beyond this its utility is doubtful.

Logically, the method to use would be to plot atomic percentages against the measured physical properties. If enough data were available, this would be the method of choice as the variation in an isomorphous series proceeds on an atomic (or ionic) basis. I have not used it here because of the lack of data although the calculated formulas in table 2 can be used as the basis for such a plot.

From the practical standpoint, the mineralogist is most concerned, in these complex series, with the variation of one or two elements such as iron. He would like to have a plot which involves the least amount of calculation and which shows the general trend. Such a plot is the one used here in figures 4 and 5. It is fully realized that this, in its way, is as artificial as the use of molecular end members. However, it does not postulate molecular end members nor molecular variation. Its virtue is that it proceeds directly from the chemical analyses, involves a minimum of calculation, and shows the general trends satisfactorily. In fact, from a numerical standpoint, plots made on any of the three systems mentioned will differ only as to scale although strictly speaking there will be a slight variation in the shape of the curves.

In the anthophyllite series, of course, a three-component diagram should be used, as alumina is significant, but lack of data precludes the usefulness of such a plot in showing the variation of the physical properties.

In figure 4 (showing the variation of nZ) the points do not fall very well on a straight line nor on a smooth curve. The line drawn shows (what is already known) that the increase in FeO, etc., raises the indices. For number 25, which falls far off the line, it shows that ferric iron has an undue influence on the indices. This specimen of Serdiuchenko (1936) from

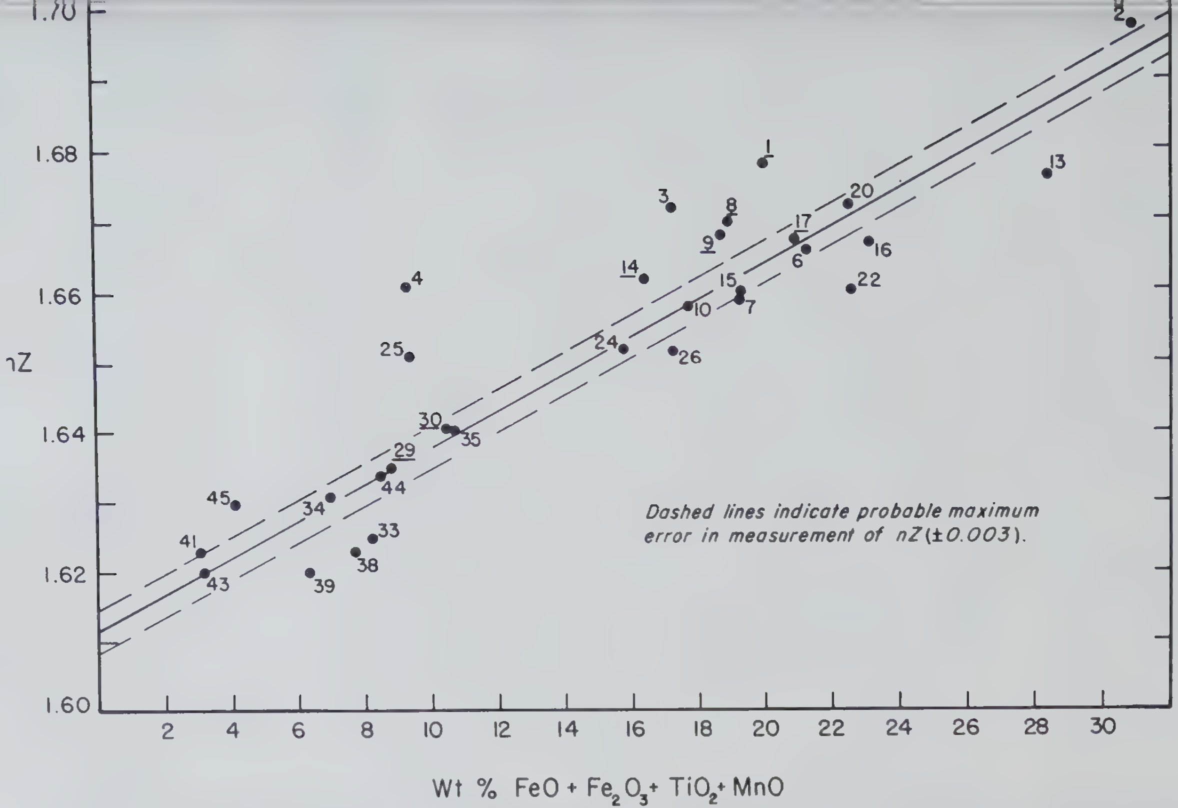

Fig. 4. The refractive index nZ plotted against chemical weights per cent of $FeO+Fe_2O_3+TiO_2+MnO$ for some anthophyllite varieties from the literature and the Montana varieties. The numbers of the Montana varieties are underlined.

Russia has 8.28% Fe_2O_3 and weighting the figures by a factor of two for ferric iron would bring it back close to the line. Number 4, the high-alumina (23.79%) specimen of Henderson from North Carolina, falls farthest from the line. Mr. Henderson sent me some of his material from the U. S. National Museum and my figures for the indices are the same as his. It must be concluded, then, that some element other than ferric or ferrous iron has increased the index. In this material Fe_2O_3 is only 0.20%, MnO is 0.16%, FeO is 9.21%, and TiO_2 was not determined. Indications are that aluminum is responsible for the high index. This belief is strengthened by the fact that the other specimens above the line are as high in alumina. These include number 1 (17.78%), number 2 (10.88%), number 3 (17.22%), number 8 (15.84%), number 9 (14.92%), and number 14 (13.26%). This is not conclusive as others (no. 6 with 14.72% Al_2O_3 and no. 10 with 15.48% Al_2O_3) fall on the line. However, number 45, near the high-magnesium end, has 5.72% Al_2O_3 (much more than other members at this end) and it falls well above the line. The concept is also strengthened by the fact that number 13 which should have about 15% Al_2O_3 in its magnesium-iron range, has only 7.63% and it falls well below the line.

Those Montana specimens (numbers underlined in the plot) high in alumina fall significantly above the line and those low in alumina, numbers 17, 29, 30, fall close to the line. When more data is available it is probable that a separate line can be drawn for the aluminian members. In general, even this two-component diagram shows an indication of the aluminum content as well as that of iron.

As *n*Z is the most significant index because, among other reasons, it is the one most easily and accurately measured in this mineral series, it is the only one plotted. Plots showing the variation of *n*Y and *n*X are unsatisfactory. They show the same general trend as *n*Z but the points are much more scattered.

The birefringence is not plotted. The points are so widely scattered that no useful curve nor straight line can be drawn. The trend, however, shows that the birefringence increases with increase of magnesium. It also shows that out of 22 specimens, 12 fall in the range 0.010 to 0.020, two are 0.020, and 8 fall in the range 0.020 to 0.025 for the D-line. The limits for all are 0.013 and 0.025. No significant effect of aluminum on the birefringence is apparent.

Optic Sign and 2V.—Winchell (1933) says " . . . the optical sign is positive in maganthophyllite and antholite; it is negative in gedrite, and perhaps also in feranthophyllite." In *Dana's Textbook* (1932) anthophyllite is said to be optically positive and gedrite optically negative. If this were true it would be a good way to identify the aluminian anthophyllites, but many if not most such members of the series are positive. Examples of these are numbers 2, 3, 6, and 10, and the Montana specimens numbers 1, 8, 9, and 14. Some of these aluminian members are negative, such as numbers 4, 12, and 20. The high-magnesium members are generally negative such as numbers 35, 40, 45 and the Montana specimen number 29, but number 30 is positive.

2V is usually large in the anthophyllites and an average figure would be above 80°. The lowest recorded are 59.3° in number 22 by Sundius (1933) from Norway and 57° in number 20 by Rama Rao (1937). In some specimens such as numbers 20 and 25 dispersion is perceptible. In both of these red > violet. The dispersion for the Montana specimens has been shown in table 9. In these red < violet in numbers 8, 14, 17, and 30; red > violet in numbers 1 and 29. In number 9 red = violet.

Orientation and Pleochroism.—In all members of the series $Z=c$ and $Y=b$. From the discussion on the optic sign it is evident that in most of the aluminian members $n\mathrm{X}$ is the acute bisectrix and in the high-magnesium ones $n\mathrm{Z}$ is usually the acute bisectrix.

Pleochroism is listed for 5 of the 26 specimens of table 10. It has been seen that 5 of the 7 Montana specimens show pleochroism. In general the aluminian and ferroan members show this property and it is probably a function of aluminum and iron. The colors exhibited are usually shades of tan and these are named subjectively by different observers as clove, clove brown, buff, cream, yellow, straw yellow, brown, brownish yellow, and so forth. This difference in color nomenclature is understandable but confusing and the best practice would be to adhere to some standard such as that of Ridgway (1912). The pleochroic colors for the Montana specimens are given in table 9 on a descriptive basis. An attempt was later made to classify two of them by the Ridgway scheme as follows:

Number 1. (CC206F)	Number 9. (Mont.40-12)
X = Y = Buffy citrine, 19′ *k*	X = Y = Light ochraceous buff, 15′ *d*
Z = Verona brown, 13″ *k*	Z = Warm sepia, 13″ *m*

This is not wholly satisfactory as the pleochroic colors are viewed in transmitted light and the colors of the Ridgway scale in reflected light. For specimens under the microscope some system based on photometric measurements would probably give good results.

Optical Limits in the Series

The optical limits in the series, on the basis of the inadequate data now available, are as follows:

n_D	F–C
$X=1.598$ to 1.674	0.017 to 0.029
$Y=1.605$ to 1.685	0.013 to 0.027
$Z=1.615$ to 1.697	0.013 to 0.022

$nZ-nX=0.013$ to 0.025

2V ranges from (−) 57° to (+) 59°

DENSITY

The relative densities* of the Montana anthophyllites together with those of some from the literature are shown in table 11 and are plotted against weight per cent of $FeO+Fe_2O_3+TiO_2+MnO$ in figure 5. The densities for the Montana material were measured for me by Dr. R. E. Folinsbee of the Canadian Geological Survey, using the 10-ml quartz pycnometer after the method of Ellsworth (1928). These figures represent relative densities corrected to 4° C. from the indicated temperatures of measurement. They can be compared to the calculated densities secured by using the unit cell volumes from *x*-ray measurement and the atomic formulas calculated from the chemical analyses, according to the formula

$$d = \frac{nM}{VN}$$

where d = density

n = number of molecules in unit cell

M = molecular weight

V = volume of unit cell (calculated from *d*-spacings based on the Siegbahn scale of *x*-ray wave lengths)

N = Avogadro's number (the old value, 6.06×10^{23})

The measured and calculated densities agree fairly closely (except for no. 17) and the range of the differences is from 0.03% for number 29 to 1.3% for number 17. Theoretically they should be no better. Bannister and Hey (1938) say that the attainable accuracy for the Ellsworth method using 12 grams of material of density 4 is ±0.06%. Fairbairn and Sheppard (1945) for 10 grams of material of density 4 place the figure at ±0.025%. For the *x*-ray method Fairbairn and Sheppard regard the cell volume as the single variable and confine their calculation of error to the powder method. Considering all errors inherent in that method of arriving at the cell constants, they show a curve T representing the maximum error for different values of θ, the angle of incidence of the x-ray beam. This curve varies from close to 0% at 90° to nearly 1.5% at 50°. They do not consider the errors in chemical analysis which would be reflected in the molecular weight in the density formula. These errors, difficult to evaluate, might easily be appreciable. For instance, a decrease in the molecular weight of number 1 of 1% changes its calculated density from 3.23 to 3.206. A ±1% error in any of the figures of the chemical analysis would not be surprising; in many of the figures it might be more.

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* A statement by Fairbairn and Sheppard (1945) is relevant here: "Although widely used, 'specific gravity' is terminologically incorrect as a synonym for relative density, and is physically incorrect as a synonym for density determined by the *x*-radiation method. 'Gravity' implies the weight of a body, i.e., the earth's attraction for it, which is not an intrinsic property, whereas by definition density is the mass of a body per unit volume, the mass being an intrinsic and invariable property."

Table 11. Density of Anthophyllite

A.—Montana specimens

Number	Measured	Calculated	Suspension
1. (CC206F)	3.277	3.23	3.25
8. (CC298)	3.261	3.23	3.25
9. (Mont.40-12)	3.245	3.25	3.23
14. (CC121)	3.259	3.22	3.25
17. (CC352C)	3.279	3.16	3.23
29. (CC200A)	3.106	3.105	3.09
30. (Mon.40-8)	3.102	3.09	3.04

Measured figures from determinations by R. E. Folinsbee. All figures are densities corrected to 4° C.

Calculated figures based on the atomic formula and the volume of the unit cell.

Suspension refers to relative densities determined by suspension in heavy liquids and subsequent measurement of the liquids on a Westphal balance.

B.—Specimens from the literature

Number	Relative Density	Number	Relative Density	Number	Relative Density
2.	3.371	20.	3.22	35.	3.093
3.	3.259	21.	3.068	38.	2.97
4.	3.178	22.	3.241	39.	2.85
6.	3.24	24.	3.157	40.	2.95
7.	3.16	26.	3.157	41.	3.006
13.	3.23	34.	3.034		

The errors quoted for the pycnometer method are probably well on

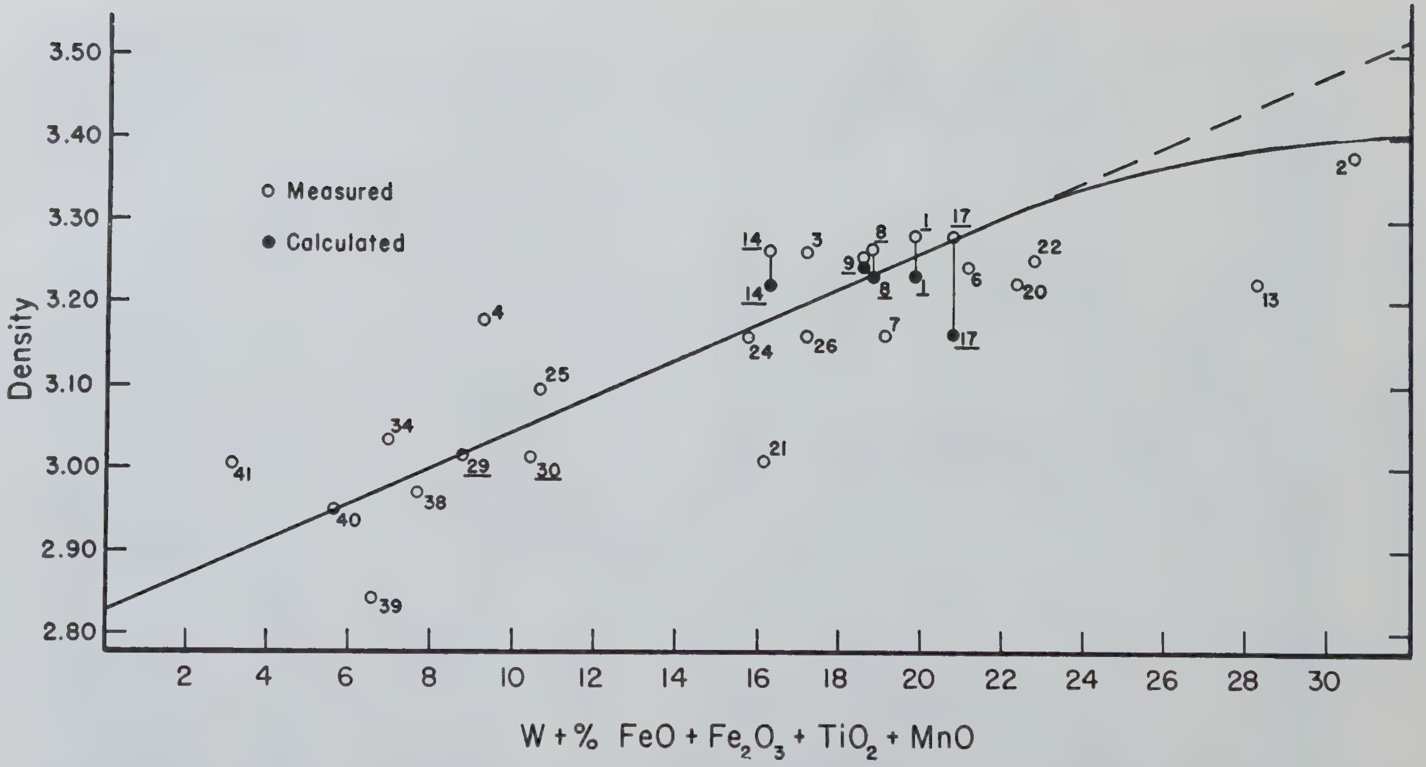

FIG. 5. Density plotted against chemical weights per cent of $FeO+Fe_2O_3+TiO_2+MnO$ for some anthophyllite varieties from the literature and the Montana varieties. The numbers of the Montana varieties are underlined. The measured and calculated figures for the Montana varieties are connected as shown; those for numbers 29 and 30 are nearly identical.

the optimistic side. The method is full of pitfalls in routine work and under the most favorable circumstances will probably produce figures no better than ±1% in actual operation. Considering the errors inherent in both the pycnometer and *x*-ray methods the correspondence shown for the Montana specimens is satisfactory.

Relative densities are also given as determined by the suspension method in which the grains are suspended in a heavy liquid (methylene iodide plus bromoform) and the density of the liquid then measured on a Westphal balance. For a modified form of this method using Clerici solution Fairbairn and Sheppard give an error of ±0.025% for material of density 4. However, in practice this method may be none too good with a complex mineral such as an amphibole. As the grains in a large collection are not of homogeneous composition a clean and sharp suspension is difficult to achieve and errors in the final result of ±1% are probably the minimum that can be expected. It is notable (table 11) that the densities measured by suspension on most of the specimens fall between the pycnometer and *x*-ray densities.

In number 17 the divergence in the measured and calculated densities is far beyond the limit of error. A careful check did not show the cause and time did not permit a more thorough investigation. The divergence could be ascribed to a faulty chemical analysis (particularly for FeO content), or the presence of a rare heavy metal in minor amount.

The value of a very accurate density measurement, considering the time and trouble which such a procedure entails, is questionable for minerals such as the amphiboles. The chemical analysis is applied to a large collection of grains and so is the pycnometric method. The calculated measurements come from *x*-ray data secured from one or two grains plus the chemical data. The resulting figures given to the third decimal place are misleading for the collection as a whole. For a study such as this, densities to the second decimal place are good enough. For number 1 in table 11, for instance, the density might have been given as 3.27 ±0.03. This predicates an error of about ±1%.

The densities shown for specimens from the literature in table 11 range from 2.85 for number 39 to 3.371 for number 2. This same range includes the Montana specimens. Theoretically, according to the curve drawn in figure 5, the possible range is 2.84 to 3.41. This should not be taken literally as the curve is not too satisfactory. The straight line as continued (dashed) in the figure might be better representative of the variation. Sufficient data is not available to decide this point. Many of the points such as numbers 4, 13, and 21 fall far off the curve which is not surprising, considering the difficulty of making good density measurements.

STRUCTURAL PROPERTIES

Morphological Crystallography

No terminated crystals of anthophyllite are known. Morphological data is given in *Dana* (1892) as follows:

> Orthorhombic. Axial ratio $a:b = 0.51375:1$, Penfield. Prismatic angle, $mm'' =$ 54°23′. Crystals rare, habit prismatic but prisms not terminated. Commonly lamellar, or fibrous massive; fibers often very slender. Also in aggregates of prisms, like actinolite.

To this is added, in *Dana's Textbook* (1932), the information that the cleavage is "prismatic, perfect; b(010) less so; a(100) sometimes distinct." Winchell (1933) says, "Crystals rare, usually fibrous; asbestiform types (always?) contain Na. Perfect (110) cleavages at 125°37′."

On anthophyllite from Edwards, St. Lawrence County, New York, Cesàro (1896) obtained $a:b:c = 0.515:1:0.285$ from the forms (100), (110), (920) and the cleavages (100), (010), (110), (021), and perhaps (011) and (031).

The most useful diagnostic crystallographic measurement in the anthophyllite series is that of the cleavage angle. For the orthorhombic amphiboles it is always near 54°30′ and for the monoclinic ones, except those in the cummingtonite series, it is near 55°30′. Cummingtonite has a cleavage angle close to that of anthophyllite, always less than 55°. Thus a simple goniometric measurement on a cleavage fragment of an amphibole will establish whether the mineral is anthophyllite or cummingtonite on the one hand (cleavage angle between 54° and 55°) or a monoclinic amphibole other than cummingtonite on the other hand (cleavage angle between 55° and 56°). Anthophyllite and cummingtonite cannot be differentiated in this way; x-ray or optical study is necessary.

The cleavage angles of the Montana specimens measured to ±05′ with the two-circle goniometer on cleavage fragments about 1 mm×0.5 mm ×0.5 mm in size are

Number 1.—(CC206F)	54°10′
Number 8.—(CC298)	54°35′
Number 9.—(Mont.40–12)	54°25′
Number 14.—(CC121)	54°21′
Number 17.—(CC352C)	54°40′
Number 29.—(CC200A)	54°06′
Number 30.—(Mont.40–8)	54°37′

In addition to these, material similar to number 20 measured 54°25′ and to number 10 measured 54°17′. The cummingtonite (CC352A) whose analysis is given in table 6 has a cleavage angle of 54°20′±05′. It is evident from these figures that there is no apparent variation of cleavage angle and chemical composition, nor can it be shown from the available data that the angle varies with any other property.

In the literature, cleavage-angle measurements on anthophyllite are scarce. Of the 46 specimens which have been most widely discussed in this study only five have had the cleavage angles measured: numbers 5 (54°41′), 12 (56°), 15 (52°41′), 16 (55°10′), and 26 (54°21′). Many figures for this angle are to be found but they have usually been secured from unanalyzed fragments.

X-Ray Crystallography

The Unit Cell.—Johansson (1930) determined the constants of the unit cells of anthophyllite, cummingtonite, and actinolite by a combination of the powder and oscillation methods on material from Falun, Norway (no. 26). Crystallographic measurement gave him $a:b=1.0267:1$ and a cleavage angle $210:2\bar{1}0=54°21'$. For the cell constants he obtained $a_0=18.52$ Å, $b_0=18.037$ Å, and $c_0=5.270$ Å which resulted in $a_0:b_0:c_0=1.02676:1:0.2922$. Using the formula $MgSiO_3$ he decided that there were 32 molecules in the unit cell and put it in the space group *Pnma*. In the powder photograph made with iron radiation he measured and indexed 47 lines.

Jansen (1933), using the rotation method on fibers from Hrubschitz, Moravia, found $c_0=5.28$ Å and from the structural data of Warren (see below) found $a_0=18.5$ Å, $b_0=17.9$ Å, and $c_0=5.27$ Å.

Warren and Modell (1930) in a classic study on material from Edwards, New York found by Weissenberg and oscillation methods that $a_0=18.5$ Å, $b_0=17.9$ Å, and $c_0=5.27$ Å and the corresponding axial ratios were found to be $a:b:c=1.035:1:0.294$. The $a:b$ ratio is double that previously assumed and the general form $(h\ k\ l)$ becomes $(2h\ k\ l)$. The cleavage prism in terms of this cell has the symbol (210) instead of (110). The number of molecules of $H_2Mg_7(SiO_3)_8$ in the unit cell is four and the space group is *Pnma*. There are 156 atoms in the unit cell and 61 parameters are necessary to define their positions.

The amphibole structure is characterized by double silicon oxygen chains; the pyroxene structure is characterized by single silicon-oxygen chains. According to Warren and Modell, "In both groups of substances, the chains lie parallel to the 'c' axis of the crystal, and are most certainly responsible for the tendency which this class of substances shows for elongation parallel to the 'c' axis. In the amphiboles the tendency toward elongation along 'c' is often carried to the extreme, and the substance exists only as a fiber. Presumably there is a reinforcing action in the double chains giving them a mechanical strength along the chain direction, which is greater than that displayed by the single chains."

There is a close correspondence in the amphibole and pyroxene unit cells:

Anthophyllite $H_2Mg_7(SiO_3)_8$	Enstatite $MgSiO_3$
Orthorhombic amphibole	Orthorhombic pyroxene
$a_0=18.5$ Å	$a_0=18.20$ Å
$b_0=17.9$ Å	$b_0=8.87$ Å
$c_0=5.27$ Å	$c_0=5.20$ Å
Tremolite $H_2Ca_2Mg_5(SiO_3)_8$	Diopside $CaMg(SiO_3)_2$
Monoclinic amphibole	Monoclinic pyroxene
$a_0=9.78$ Å	$a_0=9.71$ Å
$b_0=17.8$ Å	$b_0=8.89$ Å
$c_0=5.26$ Å	$c_0=5.24$ Å
$\beta=73°58'$	$\beta=74°10'$

From this it is seen that the *b*-axis of anthophyllite is double that of enstatite and the *a*- and *c*-axes are identical. The same relationship holds between tremolite and diopside, the corresponding monoclinic forms. The *a*-axis of anthophyllite is double that of tremolite and the *a*-axis of enstatite is double that of diopside. This can be shown graphically (after Warren) as follows:

$$\begin{tikzcd}
\text{Monoclinic amphibole} \arrow[r, "\text{double along } a"'] & \text{Orthorhombic amphibole} \\
\text{Monoclinic pyroxene} \arrow[u, "\text{double along } b"] \arrow[r, "\text{double along } a"'] & \text{Orthorhombic pyroxene} \arrow[u, "\text{double along } b"']
\end{tikzcd}$$

The structure of the unit cell of anthophyllite projected on (001) is shown in the paper by Warren and Modell (1930). A graphic representation of the amphibole and pyroxene chains is shown in the paper by Warren (1930) and the relationship between these chains and the amphibole and pyroxene cleavages is shown in the paper by Warren (1929). There is no need to reproduce them here.

X-ray measurements were made by the Weissenberg method using Cu/Ni radiation on the seven Montana specimens, an additional unanalyzed one from the Cherry Creek Area (CC384), one from Russia (similar to no. 10), and one from India, number 20. Rotation, 0-layer, and 1st-layer line pictures normal to the *c*-axes were taken of all specimens on cleavage fragments about 1 mm×0.5 mm×0.5 mm in size. The cell constants derived from these films as measured for me by Professor C. Wroe Wolfe of Boston University are, in *k*X units:

Number	a_0	b_0	c_0
1. (CC206F)	18.55	17.92	5.30
8. (CC298)	18.54	17.82	5.28
9. (Mont.40-12)	18.53	17.80	5.28
14. (CC121)	18.50	17.66	5.31
17. (CC352C)	18.55	17.95	5.31
29. (CC200A)	18.54	17.90	5.28
30. (Mont.40-8)	18.58	17.98	5.28
(ÇC384)	18.58	17.98	5.28
10. (Ka10)	18.55	17.80	5.28
20. ("Bidalotite")	18.55	18.10	5.28

This shows that c_0 and a_0 are remarkably constant. In c_0 the range is from 5.28 to 5.31 or 0.03. In a_0 it is from 18.50 to 18.58 or 0.08. In b_0, however, the range is much greater, from 17.66 to 18.10, or 0.44. It is apparent that any significant variation must lie in the figures for b_0. Plotting these against chemical weight per cent of SiO_2, or Al_2O_3, or $FeO+Fe_2O_3+TiO_2+MnO$ or any combination of ratios of these does not produce any systematic variation. It can be assumed that the cell dimensions must bear some systematic relation to composition but these figures do not reveal any. Here again more measurements are needed to show this fundamental relationship. There is no need of better measurements as the accuracy (or rather precision) attained is adequate when the x-ray, chemical, and optical data are compared.

Packing Index.—Fairbairn (1934) has developed, in a tentative way, a useful concept involving the packing index. He says, ". . . it is derived from the expression V ions/V unit cell×100, which represents the percentage of the absolute volume of one formula unit occupied by ions. The packing unit is this quantity arbitrarily divided by 10 and thus P. I. = V ions/V cell×10. The packing index of a substance therefore lies between 0 and 10, a convenient numerical range analogous to that expressing specific gravity or hardness." In discussing sources of error in the determination of the packing index he says that "all error is restricted for practical purposes to calculation of the volume of the ions in the crystal cell." There is a certain error in the figures given for ionic radii and the chemical analyses, from which are derived the atomic formulas, are fruitful sources of error. The radii for the cations are those for 6-fold co-ordination. Fairbairn believes that the average variation in radius is less than ±5% of his values which he regards as small compared to other uncertainties. Considering all the uncertainties and sources of error, he emphasizes that the packing indices are only semi-quantitative but that "correlations limited to minerals of the same type (e.g. silicates) can be made, however, with considerable confidence."

He shows that for 8 carbonates the packing index ranges from 0.7 to 4.7; for 10 sulfates from 1.2 to 5.1; for 8 phosphates from 2.3 to 5.7; for 132 silicates from 3.1 to 7.0; and for 19 oxides from 4.4 to 7.2. In general, density, hardness, and refractic index vary directly with packing index and it should be expected that a systematic variation would exist in members of a series. For this reason the packing indices of some anthophyllites whose cell dimensions were measured have been calculated, with the results shown in table 12.

TABLE 12. PACKING INDEX OF SOME ANTHOPHYLLITES

Number	Cell volume Å³	Ionic volume Å³	P. I.
1. (CC206F)	1761.81	1005.28	5.77
8. (CC298)	1744.52	1005.56	5.65
9. (Mont.40-12)	1741.52	1002.36	5.75
10. (Ka10)	1743.40	1001.20	5.74
14. (CC121)	1734.83	1001.00	5.77
17. (CC352C)	1768.08	1003.48	5.67
20. ("Bidalotite")	1772.78	996.84	5.61
29. (CC200A)	1752.25	1007.56	5.75
30. (Mont.40-8)	1761.03	1006.76	5.71

The cell volumes follow from the product $a_0b_0c_0$. The ionic volumes are calculated from the ionic radii ($V=4.19\ r^3$) of the elements appearing in the formula. Fairbairn uses the following figures for elements in the amphiboles:

Element	Ionic Radius	Ionic Volume	Element	Ionic Radius	Ionic Volume
Aluminum	.57	.80	Manganese	.91	3.14
Calcium	1.06	4.99	Oxygen	1.32	9.64
Fluorine	1.33	9.85	Potassium	1.33	9.85
Ferrous Iron	.83	2.39	Silicon	.39	.25
Ferric Iron	.67	1.26	Sodium	.98	3.94
Magnesium	.78	1.97	Titanium	.64	1.09
			OH	1.40	11.48

The packing index does not vary as much as expected in these anthophyllites. The range is from 5.61 to 5.77 and considering the uncertainties in the calculation the range is probably within the limit of error. Nevertheless, the calculations reveal some things of interest. In considering ionic volume instead of ionic radii differences in the size of the ions are much more apparent. It is generally believed that manganese and magnesium can readily substitute for each other in the anthophyllite structure as their radii are not too far apart (0.91 and 0.78) but the volumes show a large difference (3.14 and 1.97). It has been suggested in a preceding section of this paper that this may be the reason why manganese is more abundant in the cummingtonite series than in the anthophyllite series as the former is higher in iron. The volume of ferrous iron is 2.39 and manganese could more easily replace it than magnesium.

Another striking feature is that the oxygen ions account for about 85% of the ionic volume and O plus OH about 93%. Silicon accounts for only about 0.7%.

X-Ray Study of Doubtful Varieties

The identification of asbestiform anthophyllite is usually impossible by means other than *x*-ray study. Many authors have decided that their amphibole asbestos was orthorhombic because the smallest fibers under the microscope showed an apparent parallel extinction. To test the validity of this criterion an *x*-ray study of some anthophyllite asbestos was made.

Samples of the anthophyllite asbestos listed in Merrill's paper (1895) were obtained from Mr. E. P. Henderson of the U. S. National Museum and rotation pictures with Cu/Ni radiation were made normal to the fibers. These proved to be identical to the rotation pictures of numbers 14 (CC121) and 30 (Mont.40-8), for all the asbestos varieties listed in table 4 (nos. 53 to 62 inclusive). Number 91, from Salls Mountain, Georgia, had the same pattern as chrysotile and so was placed in table 6 as a doubtful species.

Zero-layer and 1st-layer line pictures were taken of the same fibers and these showed lines instead of spots; in effect they were powder pictures. Pictures were again taken of the same fibers but the fibers were kept stationary. Good rotation pictures were the result. This indicated that the *c*-axes were oriented parallel to the fibers, but that the *a*- and *b*-axes were distributed at random around the long direction. The smallest fiber (0.02 mm diameter) practical to work with gave the same results as the larger fibers (0.05 to 1 mm in diameter). This showed that the smallest individual fiber under the microscope, about the same diameter as the cross-hair of the eye piece, is a bundle of fibers.

The experiments were repeated on three amphibole asbestos specimens described by Merrill and secured from Mr. Henderson. These were USNM number 5694 from Roanoke, Virginia; number 8536 from Parkton, Maryland; and number 73462 from Chester, North Carolina. Under the microscope they all showed extinction angles $Z \wedge c$ greater than 15°. The results were the same as for the anthophyllite fibers except that the pictures from the stationary fibers were not such good rotation patterns as those of the orthorhombic specimens. The rotation pictures were identical to those made on tremolite from Edwards, New York, showing that these asbestos specimens are monoclinic amphiboles.

These tests show that although Merrill's identifications by the microscope were sound, it is possible in theory, from the random distribution of the *a*- and *b*-axes around the long direction of the fibers, to have parallel extinction in this direction in a monoclinic amphibole asbestos. That this is also true in practice will be shown in the following discussion where the *x*-ray study of doubtful varieties is described in detail.

Number 92.—This high-soda asbestos, from Coffee Creek, Trinity County, California, was described by Laudermilk and Woodford in 1930 as a "Soda-rich anthophyllite asbestos." Individual fibers under the microscope showed parallel extinction along the length and so were assumed to be orthorhombic. A rotation picture normal to the fiber length with Cu/Ni radiation was identical to that of tremolite. A similar picture of a stationary fiber gave a good rotation picture identical to the first one. As an additional check, a powder picture was taken with Cu/Ni radiation and compared with powder pictures of the anthophyllite number 30 (Mont.40-8) and the tremolite from Edwards, New York. The picture matched that of tremolite exactly. The three most prominent lines and their intensities, together with those from Johansson's data (1930) are:

Anthophyllite 30 (Mont.40-8)		Tremolite Edwards, N. Y.		Variety from Coffee Cr., Cal.		Actinolite (Johansson 1930)	
d	*I*	*d*	*I*	*d*	*I*	*d*	*I*
3.030	10	3.124	10	3.125	10	3.126	10
3.235	9	2.705	9	2.704	9	2.706	9
2.531	8	2.522	8	2.525	8	2.524	8

It is apparent that this material is monoclinic and its chemical composition shows it to be a soda-rich tremolite and not a soda-rich anthophyllite.

Numbers 86 and 87.—These two asbestos varieties, amosite, from South Africa were described by Peacock (1928) who considered them to be orthorhombic. His original specimens are in the Harvard collection under numbers 13067 (Kalkfontein, Cape Province) and 13092 (Penge, Transvaal).

Number 86 showed parallel extinction under the microscope on the smallest fiber. A rotation picture made normal to the fiber length with Cu/Ni radiation was identical to that of tremolite. A powder picture matched that of the Edwards tremolite with the three most prominent lines as follows:

Number 86		Edwards tremolite	
d	*I*	*d*	*I*
3.127	10	3.124	10
2.707	9	2.705	9
2.521	8	2.522	8

It is evident that this material is monoclinic. Its high CaO content (10.84%) and high $FeO+Fe_2O_3$ content (28.53%) make it an actinolite.

Number 87 also showed parallel extinction under the microscope. A rotation picture normal to the fiber length with Cu/Ni radiation proved to be similar but not identical to that of the anthophyllite number 30. There were slight differences in spacing in the 0-layer and a difference in the number of spots in the 1st layer. The picture was then compared with a rotation picture made with Cu/Ni radiation on the cummingtonite CC352A whose chemical analysis is given in table 7, and was identical to it. Again, as a check, powder pictures were taken of the amosite and cummingtonite and these were compared with anthophyllite and with the data of Johansson. The table below shows the results.

Anthophyllite 30 (Mont. 40-8)		Cummingtonite CC352A		Amosite 13092		Cummingtonite Johansson (1930)	
I	*I*	*d*	*d*	*d*	*I*	*d*	*I*
3.030	10	2.748	10	2.751	10	2.754	10
3.235	9	1.401	9	1.405	9	1.406	9
2.531	8	2.186	8	2.184	8	2.187	8

This comparison shows that amosite number 13092 and cummingtonite are the same and hence the material from Penge is monoclinic. Its chemical composition (39.94% $FeO+Fe_2O_3$, CaO 0.77%, MgO 5.80%) fits its designation as cummingtonite.

Numbers 90 and 84.—The asbestiform variety, number 90, from Chaveltice, Bohemia, was described by Slavik (1927) as a manganese-rich anthophyllite of which there are supposedly many examples in the manganese deposits of that region. Professor Slavik sent me some of his material so I was able to make an *x*-ray study of it. Under the microscope it showed parallel extinction along the length in the smallest fibers. A rotation picture normal to a fiber with Cu/Ni radiation did not fit anthophyllite but did fit cummingtonite. A powder picture with Cu/Ni radiation was identical to the cummingtonite powder picture:

Anthophyllite 30 (Mont.40-8)		Number 90 Chaveltice		Cummingtonite CC352A	
d	*I*	*d*	*I*	*d*	*I*
3.030	10	2.748	10	2.748	10
3.235	9	1.400	9	1.401	9
2.531	8	2.183	8	2.186	8

This material is cummingtonite and because of its high manganese content (MnO 16.10%) it belongs to the variety known as dannemorite. Such manganous varieties are common in the cummingtonite series but are not known in the anthophyllite series.

Orlov (1932) described the material listed under number 84, from Jacobemi, Bukovina, as a manganese-rich ferroanthophyllite. Professor Slavik, at my request, asked Professor Orlov for some of the original material but it had been lost in the destruction during the German occupation. By inference, however, this material, too, is cummingtonite. Savul, in his paper "Une dannemorite asbestiforme de Sarul Dornei" (1932), has described an asbestos variety with 14.39% FeO and 15.36% MnO which is monoclinic. He was able to measure the extinction angle on some of the fibers as about 14° and decided that the material belonged to the dannemorite variety of cummingtonite. Professor Slavik wrote to me that Jacobemi and a town called Dornavatra (Vatra Dornei) are "neighboring greater places next to the same manganese deposit." Sarul Dornei is about four miles southeast of Dornavatra and it is probable that it too is near the same manganese deposit. Hence we might assume that Orlov's and Sarul's asbestos came from contiguous deposits. Orlov's material has more FeO (29.34%) than Sarul's but in such a deposit the iron and manganese content of the asbestos must vary widely throughout the body. The probability is strong that Orlov's material belongs in the cummingtonite series.

Number 20.—This anthophyllite from the village of Bidaloti, Mysore Province, India, not asbestiform, was described by Rama Rao (1937) as "Bidalotite, a new orthorhombic pyroxene derived from cordierite." Mr. Rama Rao sent me some specimens of it. *X*-ray Weissenberg rotation, 0-layer, and 1st-layer line pictures with Cu/Ni radiation show it to be anthophyllite. In a number of thin sections its amphibole cleavage is well shown and its chemistry shows it to be an aluminian variety.

In the light of the foregoing identifications it is evident that no undoubted ferroanthophyllite has been found in nature. The following so-called ferroanthophyllites (including the ones discussed above) have been shown to be monoclinic amphiboles or orthorhombic pyroxenes:

Author	*Locality*	*Identity established as*
Shannon (1921)	Idaho	Actinolite (Kunitz 1930 and Winchell 1931)
Palmgren (1917)	Tunaberg, Sweden	Hypersthene (Sundius 1932)
Eckermann (1922)	Manjö Mtn., Sweden	Hypersthene (Sundius 1932)
Peacock (1928)	Cape Province, Africa	Actinolite (this paper)
Peacock (1928)	Transvaal, Africa	Cummingtonite (this paper)
Slavik (1927)	Chaveltice, Bohemia	Cummingtonite (this paper)
Warren (1903)	Rockport, Mass.	Cummingtonite (Bowen 1935)

In addition Winchell's (1931) material from the Mesabi Range, Minnesota, and that of Orlov (1932) from Jacobemi, Bukovina, are probably cummingtonites, although this has not been proved. On the basis of the x-ray study, supported by the chemical data, anthophyllite and cummingtonite do not form an isodimorphous series.

MISCELLANEOUS PROPERTIES

Color

The color of the varieties of anthophyllite show a wide range but the designation "clove brown" by Schumacher (1801) is valid for most members of the series. The purer anthophyllites are light colored such as number 30 and the asbestiform varieties. Increase in iron and aluminum darkens the color to the typical clove brown (Ridgway classification no. $17''' m$) as shown by numbers 1 and 8. Some varieties exhibit a schiller; this is shown by number 9 which changes according to the light from dusky blue green (Ridgway no. $39'' m$) to dusky orient blue (Ridgway no. $45'' m$). Some specimens are gray such as number 29, and I have an unanalyzed specimen from the Dillon Complex in Montana which is yellowish green.

The color of the analyzed Montana varieties, according to the Ridgway scheme, is as follows:

1. (CC206F)	Clove brown, $17''' m$
8. (CC298)	Clove brown, $17''' m$
9. (Mont.40-12)	Dusky blue green, $39'' m$
14. (CC121)	Avellaneous, $17''' b$
17. (CC352C)	Avellaneous, $17''' b$
29. (CC200A)	Slate gray-carbon gray
30. (Mont.40-8)	Tilleul buff, $17''' f$

Texture

The texture of anthophyllite ranges from fibrous (asbestiform) to bladed (prismatic). The fibers in the asbestos varieties can be sub-divided into hair-like fibers smaller in diameter than the cross-hairs of a microscope eyepiece. In most anthophyllites, however, the individual crystals are prisms of the order of 5 mm long and 3 mm wide. In many specimens these prisms are arranged in characteristic rosettes and such a texture is referred to by many authors as fibrous radiated.

In some varieties the prisms resemble blades and these blades may be up to 10 cm long and 3 cm wide (no. 10). A more striking example is number 29 from Montana in which the blades (or prisms) are up to 16 cm long and 8 cm wide. These are the largest known anthophyllite crystals.

As anthophyllite varieties show a good amphibole cleavage, glistening cleavage fragments are common in the hand specimen so specimens of anthophyllite usually show a high luster.

Fusion Point

The fusion point varies with the composition and there are no reliable figures for this property. Winchell (1912) quotes Brun's figures as 1230° C. for the fusion point with an inversion at 1150° C. No composition is given and the evidence for the inversion is doubtful. It is probable that the fusion point for pure anthophyllite is somewhere between 1600° and 1800° C. and from 1400° to 1600° C. for varieties high in iron (and aluminum?).

For other properties of anthophyllite such as hardness, streak, behavior before the blow pipe, and magnetic susceptibility, the reader is referred to the standard textbooks.

Occurrence and Rock and Mineral Association

The distribution of anthophyllite and the rocks and minerals with which it is associated are shown in table 13. This table is confined to the 46 analyzed varieties listed in table 2 in the section on chemical data. The data on distribution and rock and mineral association is arranged alphabetically by countries and the countries are sub-divided by provinces or states. The varieties are identified by analysis numbers as in table 2. The geologic age of the enclosing rocks is given but it must be emphasized that this may not be the age of the formation of the anthophyllite.

It is apparent that anthophyllite is widespread, particularly in the pre-Cambrian rocks. It is strictly a metamorphic mineral as no varieties are known that have crystallized from a magma.

The paragenesis of anthophyllite has been studied by many workers (Eskola, Tilley, Bugge, and others) but due to insufficient data these studies have not been particularly satisfactory. No useful purpose would be served by quoting here from the voluminous literature on the subject.

(*For Conclusions see page 315*)

TABLE 13. OCCURRENCE AND ROCK AND MINERAL ASSOCIATION OF ANTHOPHYLLITE

Country	Province or state	Analysis no. (see table 2)	Rock and mineral association	Geologic age
Australia	Southwest Division	7	At Bullsbrook in gabbro pegmatite; with plagioclase.	Pre-Cambrian
Austria	Tyrol	19	No information.	?
Canada	Ontario	5	In Haliburton Co. in amphibolite with garnet, cordierite, feldspar.	Pre-Cambrian
Czechoslovakia	Bohemia	31	At Schützendorf in serpentine with magnetite and olivine.	?
Finland	Oulun	38, 39	At Paakila as anthophyllite nephrite with talc and serpentine.	Pre-Cambrian
		42	At Paakkilanniemi as asbestos fibers in gneiss.	Pre-Cambrian
		44	At Tiilikainen as asbestos fibers in gneiss.	Pre-Cambrian
	Porin	13, 16	At Träskböle as radiating rosettes in gneiss with cordierite.	Pre-Cambrian
	Viipurin	2	At Kalvola in garnet amphibolite with garnet, cummingtonite, plagioclase, and biotite.	Pre-Cambrian
France	Ille et Vilaine	37	At St. Germain l'Hermite in nodulose serpentine with calcite, opal, and talc in granite gneiss.	Pre-Cambrian
Great Britain	Sutherland	6	At Strathy in the schists and granulites of the Moine series with cummingtonite, oligoclase, biotite, quartz, magnetite.	Pre-Cambrian
India	Mysore	20	At Bidaloti in biotite-cordierite-hypersthene granulite.	Pre-Cambrian
Italy	Island of Elba	40	At S. Piero in Campo in serpentine with talc, magnetite, spinel.	Pre-Cambrian
Madagascar		21	At Mt. Tzilaizina in crystalline schist with cordierite and quartz.	Pre-Cambrian
		23	In actinolite schist as asbestos.	Pre-Cambrian
Norway	Buskerud	27	At Kongsberg in mica schists, gneisses, and amphibolites and in the fahlbands with quartz, feldspar, hornblende, garnet, chalcopyrite, pyrite, pyrrhotite.	Pre-Cambrian
	Sor Trondelag	22	At Trondhjem in amphibolite with cummingtonite.	Pre-Cambrian
	Telemark	18	At Bamble as at Kongsberg.	Pre-Cambrian
		24	At Kjernerud as at Kongsberg.	Pre-Cambrian

TABLE 13—(*continued*)

Country	Province or state	Analysis no. (see table 2)	Rock and mineral association	Geologic age
		46	At Vormlitjern in gneiss and amphibolite with cordierite, plagioclase, hornblende, garnet.	Pre-Cambrian
Sweden	Jamtland	26	At Falun, "as slender needles imbedded in pyrite."	Pre-Cambrian
Tanganyika	Morogoro	36	In the M'Sembe, M'Kundi and N'Guru Ya N'Dege Hills as bands in gneiss and schist.	Pre-Cambrian
U.S.S.R.	Caucasus	25	On the banks of the Malaya Laba River in serpentine with talc.	Pre-Cambrian (?)
	Karelia	3, 10	At Shueretsky in coarse-grained gneiss with garnet, quartz kyanite, plagioclase, biotite.	Pre-Cambrian (?)
	Urals	32	At Kochnevsky as asbestos in talc.	Paleozoic (?)
		45	At Mramorsky as above.	?
		34	At Miask. No further information.	?
United States	Connecticut	11	At Haddam, Middlesex County, with cordierite in schist bordering a beryl-tourmaline pegmatite.	Paleozoic (?)
	Idaho	33	At Kamiah, Lewis County, as asbestos with olivine, talc, pyrite, and carbonates in lenticular bodies replacing dunite.	Pre-Cambrian
	Massachusetts	12	At Warwick, Franklin County, with talc and rutile in soapstone.	Paleozoic
		15	At Chesterfield, Hampshire County, with garnet, mica, and tourmaline.	Paleozoic
	Montana	30	In the Dillon Complex in Beaverhead and Madison Counties with actinolite, serpentine, enstatite, clinohumite, spinel, annabergite, magnetite.	Pre-Cambrian
		9	Along the borders of the Complex in schist with quartz, plagioclase, spinel.	Pre-Cambrian
		14	In the Ruby Dam Area, Madison County in amphibolite with garnet, quartz, plagioclase, chlorite, rutile.	Pre-Cambrian
		1, 17	In the Cherry Creek Area, Madison County, in amphibolite with garnet, quartz, feldspar, cummingtonite.	Pre-Cambrian
		8	Same as above, with staurolite.	Pre-Cambrian
		29	Madison County; in isolated boulders with chlorite.	Pre-Cambrian

TABLE 13.—(*continued*)

Country	Province or state	Analysis no. (see table 2)	Rock and mineral association	Geologic age
	New York	41, 43	At Edwards, St. Lawrence County, with nearly pure tremolite in schist.	Pre-Cambrian
	North Carolina	4	At Masons Creek, Franklin County, with rhodolite, hypersthene, and biotite in a dike (originally eclogite) in schist.	Pre-Cambrian
		35	At Corundum Hill, Macon County, with vermiculite, talc, actinolite, albite, corundum, chlorite, enstatite, in a zone bordering dunite.	Paleozoic
		28	At Bakersville, Mitchell County, in dunite boulders as above.	Paleozoic (?)

CONCLUSIONS AND SUGGESTIONS FOR A REVISION OF THE SERIES

From this study the following main conclusions can be drawn:

1. The anthophyllite and the cummingtonite series are not isodimorphous.

2. The anthophyllite series is a 3-component one of limited isomorphism involving chiefly magnesium, iron, and aluminum. Iron (or $Fe'' + Mn''$) replaces magnesium from about 5% to about 50% of complete replacement calculated on the atomic basis. Aluminum replaces silicon nearly up to 2 atoms and the same is true of its replacement of Mg, Fe''; thus the formula $H_2Mg_5Al_2Si_6Al_2O_{24}$ is nearly fulfilled.

3. Manganese is not important in the series. It is notable that many cummingtonites are high in manganese. Aluminum, high in many anthophyllites, is not a major constituent of the cummingtonite series.

4. Calcium is present in most anthophyllites, the average amount being about one half of one per cent; about the same amount of sodium is also present in many anthophyllites; potassium is present in negligible amounts in some anthophyllites and is absent in the rest.

5. The identification of anthophyllite is not certain unless based on *x*-ray methods. This is particularly true of the asbestiform varieties.

6. There is not enough data to determine adequately the relations of the physical properties and the composition of anthophyllite. Further study should be made of the series; this can be done profitably only when more data as to the physical properties and composition is secured. Such information, accompanied by field observations, can then be made the basis of a paragenetic study of the whole series. I hope to present soon a study of the paragenesis of the Montana varieties described in this paper.

The name anthophyllite should be used for all members of the series. Chemical suffixes as proposed by Schaller (1930) can be used to indicate any variation in the composition if known. Aluminum-rich members should be called aluminian anthophyllite and the term gedrite should be dropped. Members rich in ferrous iron should be called ferroan anthophyllite; ferrian anthophyllite would refer to members rich in ferric iron and thus the term would replace picroamosite which should be discarded. As amosite is not anthophyllite but refers to at least two different monoclinic amphiboles it should be restricted to commercial usage where it serves a useful purpose. Ferroanthophyllite and other synonyms denoting very high-iron anthophyllites should be dropped.

Under this scheme all varieties of orthorhombic amphibole would have one name, anthophyllite, which would be, as now, the name of the series also.

The series can be characterized by the general formula

$$X_7Y_8O_{22}(OH, F)_2$$

where X is chiefly Mg, Fe'', Al and in minor part Mn, Ti, Fe''', Ca, Na, K. Y is chiefly Si and in part Al and where in X the maximum amount of Al is $(Mg, Fe'')_5Al_2$; the maximum amount of Fe'' is about $(Mg_{3.5}Fe_{3.5})$ and in Y the maximum amount of Al is (Si_6Al_2).

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My wife, Mary Collins Rabbitt, has patiently acted as critical editor and typist of the manuscript.

Note

A description by Yamada (1943) of anthophyllite from Wariyama, Iwate Prefecture, Japan, was called to my attention by Mr. Michael Fleischer after the manuscript of this report was finished. The variety is in Paleozoic hornfels ("Senmaya Contact Rocks") with quartz, plagioclase, cordierite, and biotite. Accessory minerals are apatite and tourmaline. Optics are: $nX = 1.664$, $nY = 1.671$, $nZ = 1.679$; (+) $2V = 81°$, red < violet. Chemical analysis is SiO_2 48.80, TiO_2 0.47, Al_2O_3 8.10, Fe_2O_3 0.11, FeO 25.07, MnO 0.24, MgO 13.48, CaO 0.50, Na_2O 0.25, H_2O (+) 2.74, H_2O (−) 0.06; Total 99.82.

On the basis of 24 (O,OH) my calculation of the formula is $(Ca_{0.8}Na_{0.12})$ $(Mg_{2.95}Fe''_{3.07}Mn_{0.02}Ti_{0.04}Al_{0.52})$ $(Si_{7.15}Al_{0.85})$ $(O_{21.32}OH_{2.68})$, and in this $X = 6.80$, (Mg, Ca, Na)/Fe'', Mn, Ti $= 3.15/3.13$, so this is a ferroan anthophyllite near the iron limit of the series.

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CHARTING FIVE, SIX, AND SEVEN VARIABLES ON HYPERTETRAHEDRAL FACES

JOHN B. MERTIE, JR.[1]

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ABSTRACT

Three variables may be charted in a triangle by the use of trilinear coordinates, and four variables in a tetrahedron by means of quadriplanar coordinates. Negative trilinear and quadriplanar coordinates may also be used to advantage. These unique properties of the triangle and tetrahedron suggest that similar properties exist for hypertetrahedra of n dimensions.

By mathematical generalization, it is possible to predict the number of vertices, edges, triangular faces, tetrahedra, and hypertetrahedra that bound an n-dimensional hypertetrahedron. A tabulation of these boundaries, up to the ninth dimension, is given. The number of vertices in each hypertetrahedron corresponds to the number of variables that may be charted within it. Hypertetrahedra of 4, 5, and 6 dimensions, having 5, 6 and 7 vertices, are bounded respectively by 10, 20, and 35 triangular faces.

Four variables may be charted in a tetrahedron by constructing geometrically or by deducing analytically the resulting surface, which may then be shown either in perspective or by projection as a topographic map. Another method is to develop the tetrahedron onto a plane, and merely to plot the triads 123, 124, 134, and 234, each recomputed to 100 per cent. The first method is inapplicable to hypertetrahedra, and the second method may not be exactly applied, as hypertetrahedra can not be developed. The triangles bounding the hypertetrahedra, however, may be arranged empirically, so as to constitute a compound system of trilinear coordinates for charting the triads $1, 2 \cdots (v-1), 3 \cdots v, 2, 3 \cdots (v-1), 4 \cdots v, 3, 4 \cdots (v-1), 5 \cdots v$, etc., where v means both vertices and variables.

Coordinate systems of this kind have been prepared for charting 5, 6, and 7 variables. Some choice exists in the arrangement of the triangles, but the factor of compactness practically eliminates all but one arrangement. Such coordinates may be given algebraic meanings within individual triangles, but not between them. The composite charts, however, afford geometrical pictures which, if conventionalized, may be as effective as a true system of analytical coordinates.

Four analyses of platinum metals are used to illustrate the charting of 6 variables on the 20 triangular faces of a hypertetrahedron of 5 dimensions. Variable scales are required for best delineation of the resulting curves, and methods are given for producing such changes in scale.

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INTRODUCTION

Physical measurements commonly involve three or more components or variables, and the relations between them are most readily grasped if they can be shown in graphic form. Numerous systems of 3-dimensional coordinates have been devised for this purpose, but 3-dimensional rectangular cartesian coordinates are generally used. Any equation in three variables may thus be charted, but an equation in four variables presents difficulties. A 3-dimensional surface may be projected orthogonally onto a plane, thus reducing by one its number of dimensions, and producing a topographic map. Similarly, but by the use of analytical methods, an equation in four variables, representing a 4-dimensional continuum, may be projected into three dimensions; but the resulting representation will comprise a series of 3-dimensional surfaces, as numerous as the contours on a topographic map. Graphs of this kind are impracticable for four variables, and are almost impossible for five or more variables.

All systems of coordinates for charting more than three variables are impaired by shortcomings of this, or some other kind. Partial success has been achieved by combining components, by making multiple curves or diagrams, by the use of nomograms, and by other devices, but restrictions of some sort are invariably required. One of the limitations that may be tolerated, particularly in charting chemical analyses, is that the sum of the variables shall equal unity, or 100 per cent. With this limitation, three variables may be charted within a triangle, and four within a tetrahedron. This unique property, possessed by the triangle and tetrahedron, is also possessed by hypertetrahedra of *n* dimensions, so that any number of components whose sum is unity may theoretically be charted. But it is impossible to depict graphically such *n*-dimensional continua, so that further restrictions and compromises must be made. This paper is an exposition of one method for utilizing the concept of hypertetrahedral charting.

TRILINEAR AND QUADRIPLANAR COORDINATES

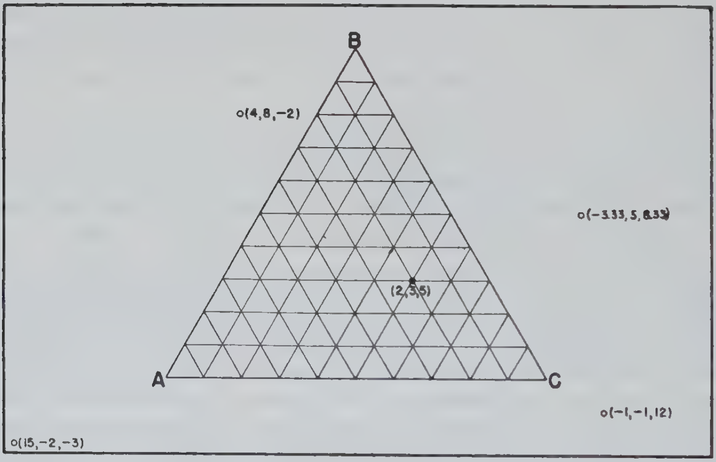
Trilinear coordinates are so commonly used in the graphic representation of 3 variables that no description of this usage seems necessary. Little application is made, however, of the analytical geometry of trilinear coordinates, whereby trilinear equations may be written to show relationships between curves that are experimentally derived and graphically presented. American textbooks on elementary analytical geometry are particularly reticent on this subject. Two elementary statements and one complete treatise on trilinear coordinates, all of British origin, are cited herewith:

Smith, Charles, An elementary treatise on conic sections by the methods of coordinate geometry. Macmillan & Co., Ltd., London, pp. 341–389 (1919).

Loney, Sidney L., The elements of coordinate geometry: part II, trilinear coordinates. Macmillan & Co., Ltd., London, 228 pp. (1923).

Whitworth, William A., Trilinear coordinates and other methods of modern analytical geometry of two dimensions. Deighton, Bell & Co., London, 506 pp. (1866).

Trilinear coordinates are built about any 3 non-parallel non-concurrent lines in a plane, which intersect to form a triangle of reference, commonly called a trigon. This triangle may have any shape, but both graphics and analysis are simplified if an equilateral triangle is used. Such a trigon is illustrated by Fig. 1. The three coordinates of a point, written as (α, β, γ), are measured on normals to the edges, drawn in the direction of the opposite vertices for positive values, and in the reverse direction for negative values. One or two coordinates may be negative, but not three.



POSITIVE AND NEGATIVE TRILINEAR COORDINATES

Fig. 1

If the sides of a trigon are represented as $\mathfrak{a}$, $\mathfrak{b}$, and $\mathfrak{c}$, and its area as Δ, it is readily shown that

$$\frac{\mathfrak{a}\alpha + \mathfrak{b}\beta + \mathfrak{c}\gamma}{2\Delta} = 1. \tag{1}$$

Any term of any trilinear equation may therefore be multiplied one or more times by the left side of equation (1), without changing the value of the equation. Hence all algebraic trilinear equations are, or can be rendered, homogeneous. Thus the general equations for a straight line and for a conic section are respectively as follows:

$$l\alpha + m\beta + n\gamma = 0$$

$$a\alpha^2 + b\beta^2 + c\gamma^2 + 2f\beta\gamma + 2g\gamma\alpha + 2h\alpha\beta = 0.$$

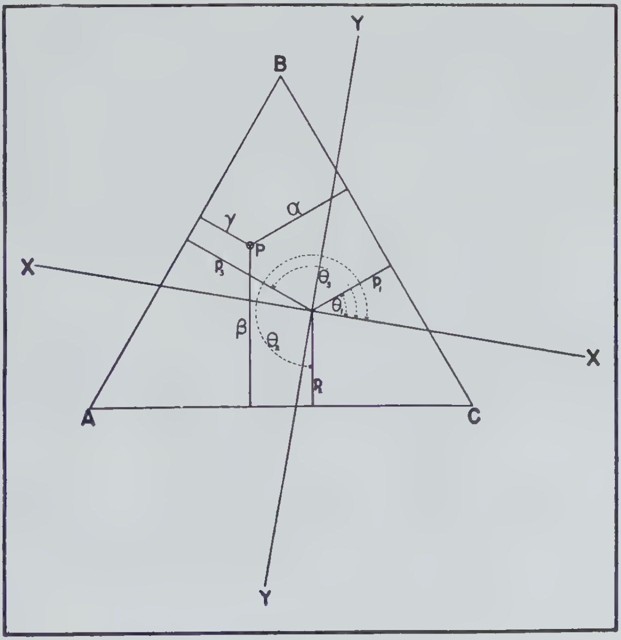
Trilinear coordinates are readily transformed to rectangular cartesian coordinates by means of the following formulae:

$$\alpha = x \cos \theta_1 + y \sin \theta_1 - p_1 \tag{2}$$

$$\beta = x \cos \theta_2 + y \sin \theta_2 - p_2 \tag{3}$$

$$\gamma = x \cos \theta_3 + y \sin \theta_3 - p_3 \tag{4}$$

where p_1, p_2, and p_3 are the trilinear coordinates of the origin of cartesian coordinates, and θ_1, θ_2, and θ_3 are the angles which normals from a point to the sides of the trigon make with the X axis. These relationships are shown in Fig. 2. For further information on trilinear coordinates, the reader is referred to the publications cited above.



TRANSFORMATION OF COORDINATES

FIG. 2

Quadriplanar coordinates bear the same relation to a tetrahedron as trilinear coordinates do to a triangle. Commonly a regular tetrahedron of reference is used, having equilateral triangular faces. Positive coordinates are measured on a normal from each face in the direction of the opposite apex; negative coordinates are measured in the reverse direction. One, two, or three negative coordinates may exist, but not four. All algebraic quadriplanar equations are, or may be rendered, homogeneous by the same method heretofore shown for trilinear coordinates; and the transformation to 3-dimensional rectangular cartesian coordinates is made by the use of four formulae analogous to (2), (3), and (4).

APPLICATION OF NEGATIVE COORDINATES

The point (2, 3, 5) is one of those charted in Fig. 1. Its coordinates may be considered to represent the composition of a rock composed of 2 parts quartz, 3 parts feldspar, and 5 parts mafic minerals. Suppose another rock exists whose composition is 2 parts nepheline, 3 parts feldspar, and 5 parts mafic minerals. As quartz and nepheline are incompatible, the mode of this alkaline rock might be given as $(-2, 3, 5)$. But the sum of these numbers is 6 instead of 10, wherefore each must be multiplied by $\frac{10}{6}$ to produce the true coordinates $(-3.33, 5, 8.33)$. This point may then be charted, as shown in Fig. 1, to represent the composition of the alkaline rock. If in some comagmatic region, other igneous rocks exist whose modes lie between or beyond the points (2, 3, 5) and $(-3.33, 5, 8.33)$, they may also be charted, and their loci may be joined by a fitted curve whose trilinear equation can be written with reference to the trigon *ABC*. This would not be possible if the alkaline rocks had been charted with reference to a contiguous trigon, say *ACD*.

The expansion shown above, to obtain coordinates whose algebraic sum equals 10, is more generally accomplished by multiplication by $L/[S]$, where L is the number of divisions into which each side of the trigon is divided, and $[S]$ is the absolute value of the algebraic sum of the original ratios of the mode. Attention is called to the fact that α, β, and γ become points at infinity if $S=0$. The original ratios may be recovered from the expanded coordinates by means of the equation

$$r = \frac{L\alpha}{[\alpha] + [\beta] + [\gamma]}$$

where r refers to one of the three original ratios of the mode, and α refers to its coordinate. Similar formulae, of course, are used for s and t, the other two ratios of the mode, and for β and γ, their derived coordinates. The use of negative coordinates thus permits the analytic charting of four variables in a plane, if two of these variables are incompatible; and of five variables in a plane, if two pairs of variables are incompatible.

Negative quadriplanar coordinates may also be used to advantage, as shown in the following example. The six platinum metals, when analyzed, are first treated in hot aqua regia, but an insoluble residue remains that must be fused with a flux. The soluble and insoluble fractions are separately analyzed, and are afterwards combined in proper proportions to give the complete analysis. The soluble fraction contains platinum, iridium, rhodium, and palladium; the insoluble fraction contains platinum, iridium, rhodium, osmium, and ruthenium. Palladium is thus absent from the insoluble fraction, and osmium and ruthenium are absent from the soluble fraction. The analysis of the soluble fraction may be charted in quadriplanar coordinates as a point within a tetrahedron of reference whose vertices are Pt, Ir, Rh, and Pd. By combining the hexagonal elements osmium and ruthenium, and considering them as incompatible with palladium, the component Os-Ru may be plotted as negative in relation to the vertex Pd. Thus the analysis of the insoluble fraction may be represented as a point outside the same tetrahedron of reference. A series of such analyses can therefore be represented as two surfaces, one inside and the other outside the tetrahedron; and thereafter both surfaces may be shown as topographic maps. Similarly six variables may be charted in quadriplanar coordinates, if two pairs of variables are incompatible; and seven variables may be charted if three pairs are incompatible.

HYPERTETRAHEDRAL CHARTING

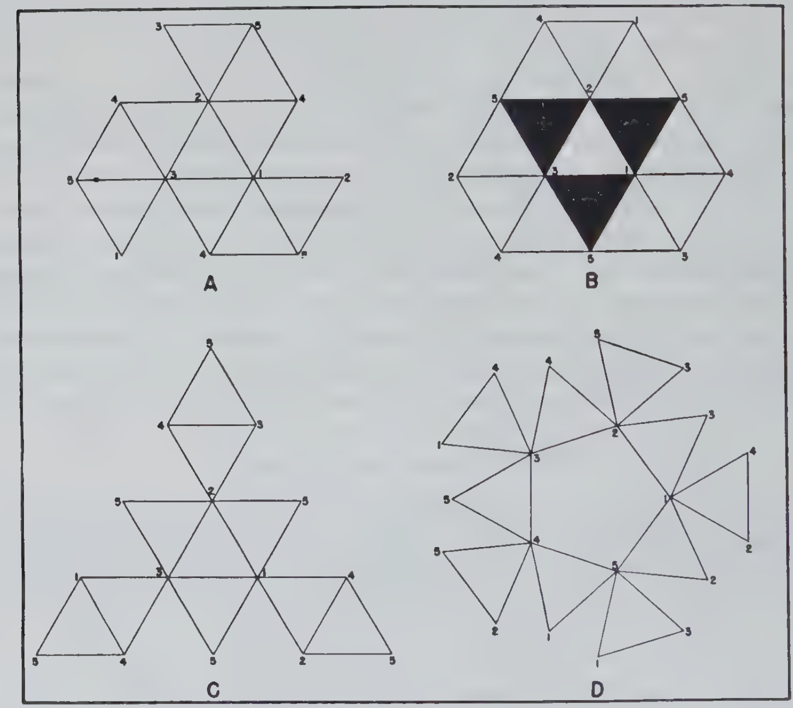
From the properties of the triangle and the tetrahedron, it follows by mathematical induction that *n* variables may be charted in hypertetrahedra of *n*-1 dimensions. The boundaries of such hypertetrahedra, up to the ninth dimension, are shown in the following tabulation:

DIMENSIONS OF HYPERTETRAHEDRA

Boundaries	Fourth	Fifth	Sixth	Seventh	Eighth	Ninth
Vertices	5	6	7	8	9	10
Edges	10	15	21	28	36	45
Triangles	10	20	35	56	84	120
Tetrahedra	5	15	35	70	126	210
H_4	1	6	21	56	126	252
H_5	0	1	7	28	84	210
H_6	0	0	1	8	36	120
H_7	0	0	0	1	9	45
H_8	0	0	0	0	1	10
H_9	0	0	0	0	0	1

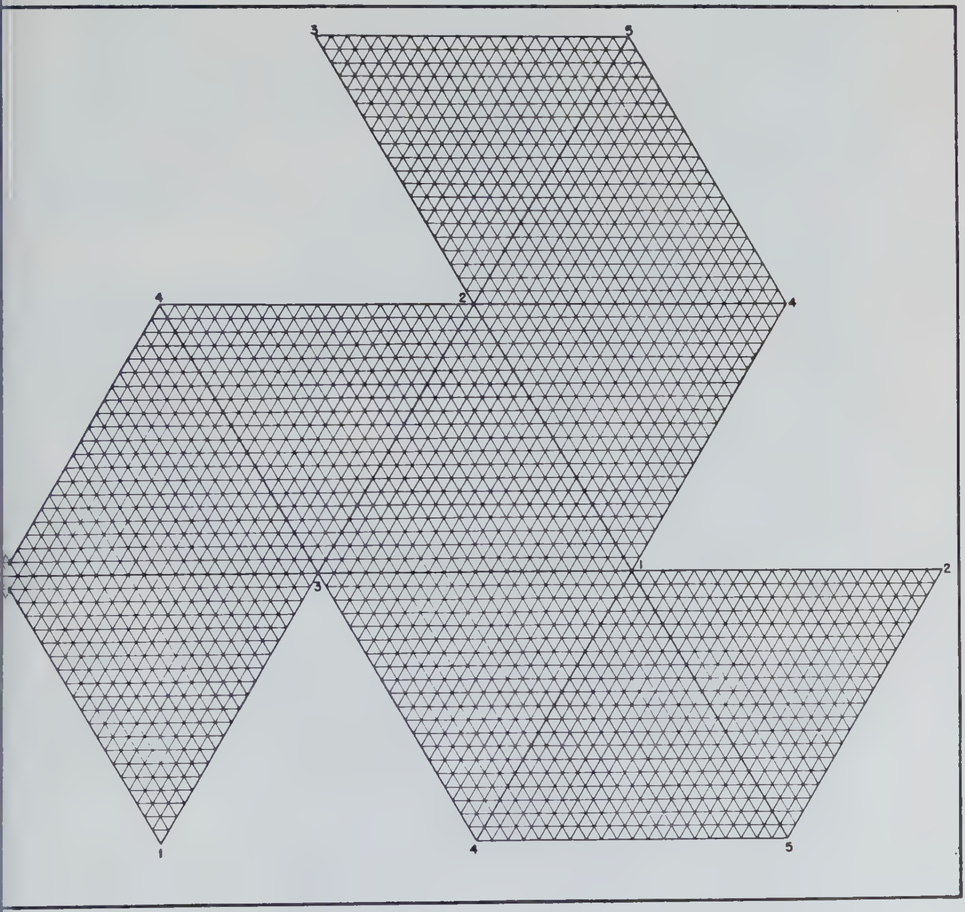
In this tabulation, H_4, H_5, etc. refer to hypertetrahedra of the fourth, fifth, and higher dimensions.

The charting of continua, and their fitting to experimental data, are possible and feasible by analytical methods, but unfortunately no practical method exists for a graphic presentation of the results. Compromises must therefore be sought. Consider the problem of charting 5 variables. At first sight it might seem that the best method would be to utilize quadriplanar coordinates, charting the data in the tetrahedra that bound a hypertetrahedron of 4 dimensions. But there are 5 such tetrahedra, so that it would be necessary to chart a surface in each of the tetrahedra 1234, 1235, 1245, 1345, and 2345, only two of which could have common bases. This would be a laborious procedure that few would attempt. An alternative would be to develop the 5 tetrahedra, preserving each developed tetrahedron as a unit, and showing the triad relationships on 20 triangular faces. But this is wasteful of space, because 10 faces bound a hypertetrahedron of 4 dimensions, and therefore only 10 triangles need to be shown to convey the same amount of information.



FOUR ARRANGEMENTS OF TEN TRIGONS

FIG. 3



TRILINEAR COORDINATES FOR FIVE VARIABLES

Fig. 4

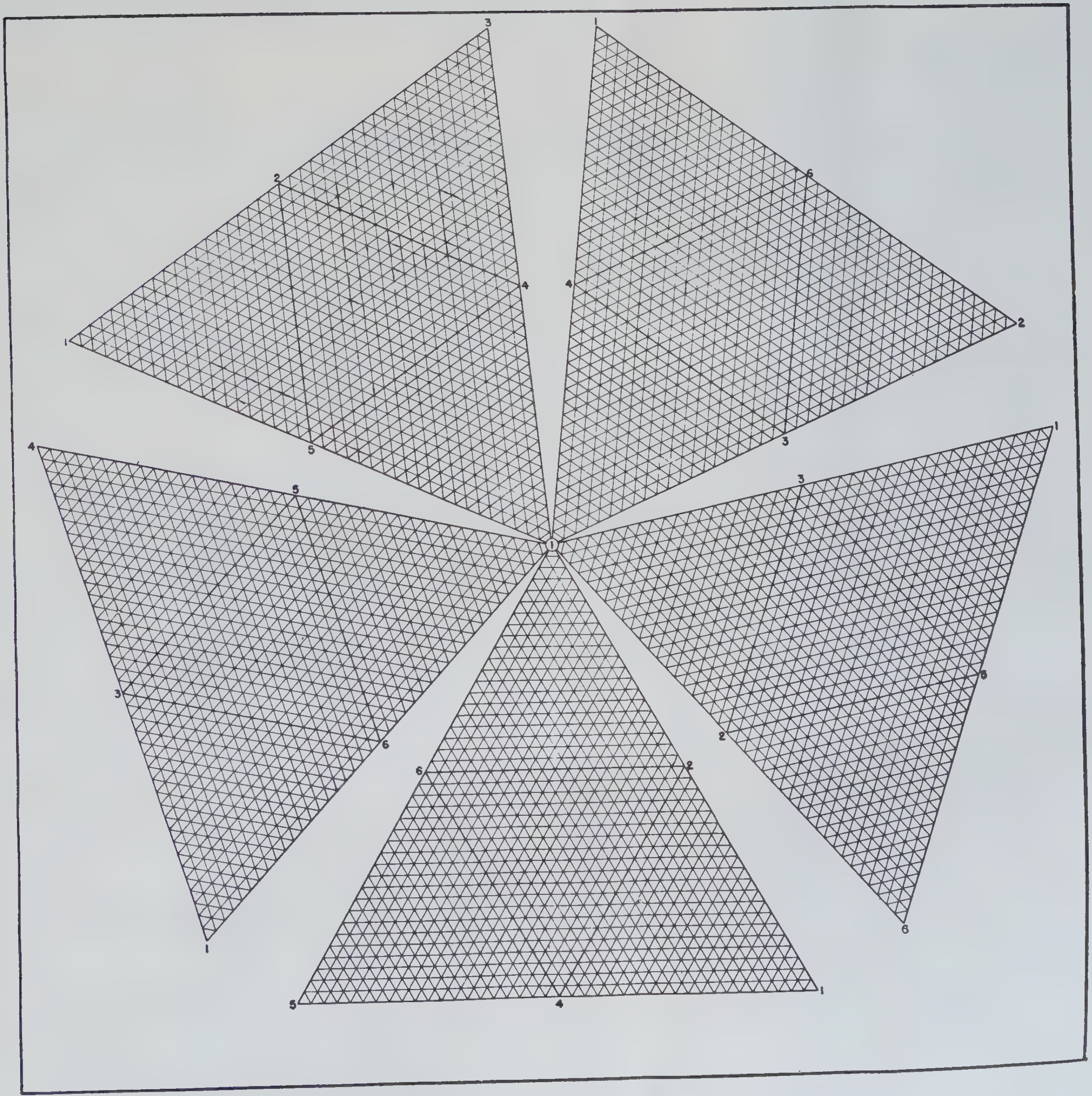
The simplest arrangement for the 10 triangles 123, 124, 125, 134, 135, 145, 234, 235, 245, and 345 is in rows and columns, as in a rectangular array, but such an assembly would be uneconomical of space, and would show no relationships between adjoining triads. When assembled as a single diagram, however, some choice still exists in the arrangement of trigons, but conservation of space largely eliminates such choice. Figure 3, for example, shows 4 ways in which the 10 trigons mentioned above may be arranged. Arrangements *C* and *D* require more space than *A* or *B*, and therefore for a diagram of given size, the trigons of *C* and *D* would have to be smaller. Arrangements *A* and *B* have the same size and shape, but *A* preserves one developed tetrahedron, whereas *B* does not. Arrangement *A* is obviously the best one.

The hypertetrahedra of higher dimensions show further difficulty in the utilization of quadriplanar coordinates. It will be noticed, as the number of variables increases, that the number of bounding tetrahedra increases faster than the number of bounding triangles, so that the labor of charting surfaces increases progressively. Thus for 7 variables, the number of tetrahedra equals the number of triangles; but for more than 7 variables, the tetrahedra are more numerous than the triangles. All these considerations have impelled the writer to the use of compound systems of trilinear coordinates, wherein the bounding triangles are shown only once.

THE CHARTS

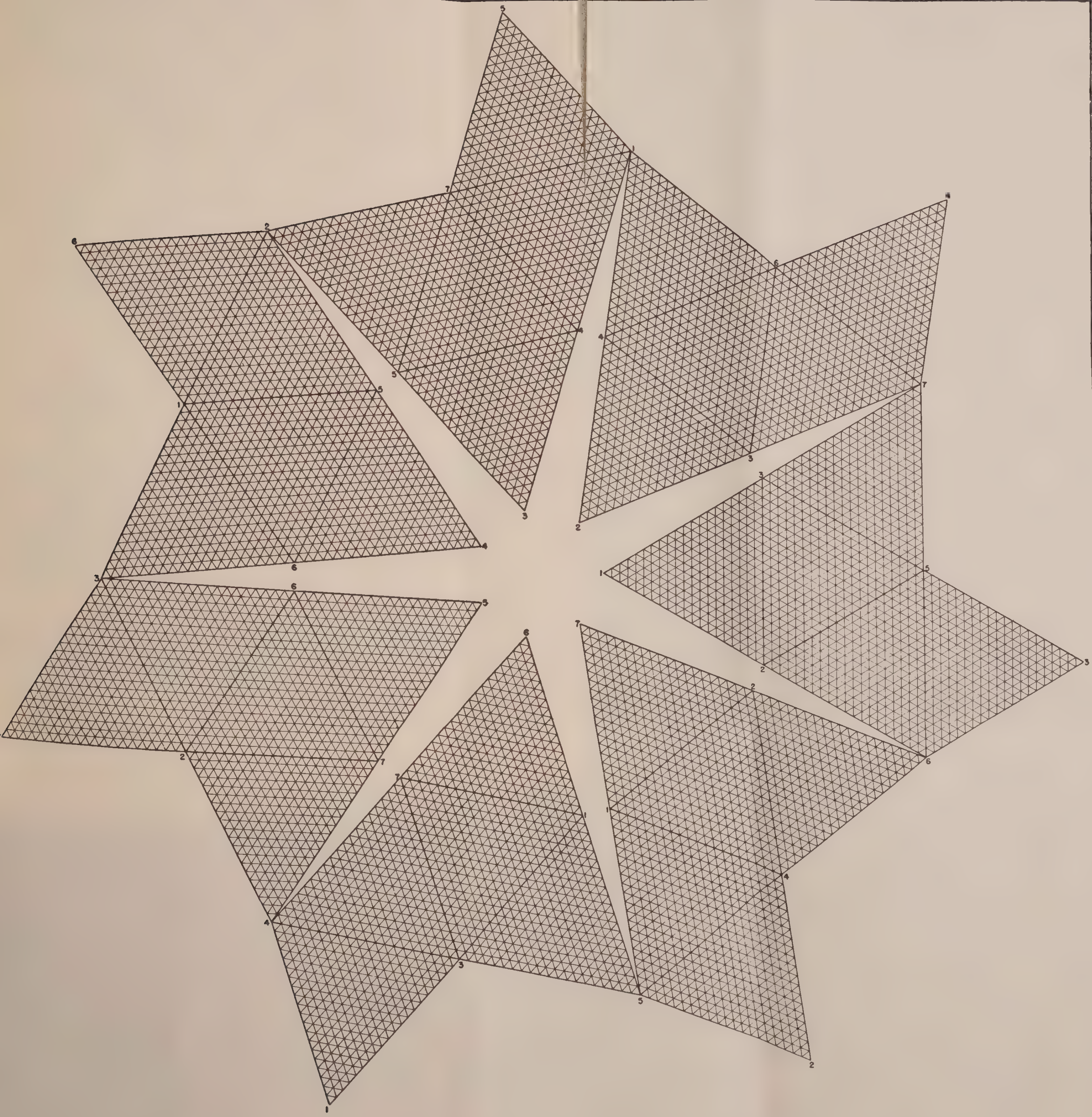
Figures 4, 5, and 6 show the most compact arrangements of the triangular faces that bound hypertetrahedra of 4, 5, and 6 dimensions; and these render possible the charting, respectively, of 5, 6, and 7 variables. A chemical analysis, for example, is computed to total unity, or 100 per cent, after which all possible triads are also recomputed to unity. These values are then plotted in their respective trigons.

One of the difficulties in any system of charting is scale. Certain sets of values may be well represented at one scale, whereas others, plotted at the same scale, will fail to show distinct relationships. This is overcome in cartesian coordinates by a change in scale of the ordinates or abscissae, or both. The same problem necessarily occurs in trilinear coordinates, where several sets of coordinates that should delineate a curve, may be so near to one another that the resulting curve is too small for satisfactory inspection. Amplification of the curve is therefore desirable, but such amplification must not result in the charting of points outside the trigon in which their coordinates belong. The accomplishment of this objective is found to depend upon the minimum value of the largest coordinates among the sets to be charted within a single trigon.



TRILINEAR COORDINATES FOR SIX VARIABLES

FIG. 5



TRILINEAR COORDINATES FOR SEVEN VARIABLES

Fig. 6

The relationship between magnification and coordinates is given by the following formula:

$$Mx - M + 1 = 0 \tag{5}$$

where M is the possible magnification of scale, and x is the minimum value of the largest coordinate in a number of sets. Thus it may happen that the minimum value of the largest coordinate in several sets is not less than .80, from which it follows that the maximum amplification of scale is 5. Attention is directed to the fact that it is immaterial whether the largest coordinates in the sets are α, β, or γ, or a mixture of these. Some of the possible magnifications are shown below:

Possible Magnification (M)	Minimum Value of Maximum Coordinates (x)
$M=100$	$x \geqq .990$
50	.980
25	.960
15	.933
10	.900
9	.889
8	.875
7	.857
6	.833
5	.800
4	.750
3	.667
2	.500
1½	.333

The value of a magnified maximum coordinate is obtained from the following formula:

$$V = LMC - L(M - 1) \tag{6}$$

where C is the numerical value of the maximum coordinate, L is the number of divisions of each side of the trigon, M is the magnification, and V is the required value of the maximum coordinate in the magnified scale. Thus, if $C = \alpha = .824$, $L = 20$ (as in Figs. 4, 5, and 6), and $M = 5$ (as indicated from the preceding tabulation), the value of V will be 2.4 divisions of the scale. The value of the magnified minor coordinates is obtained from the equation:

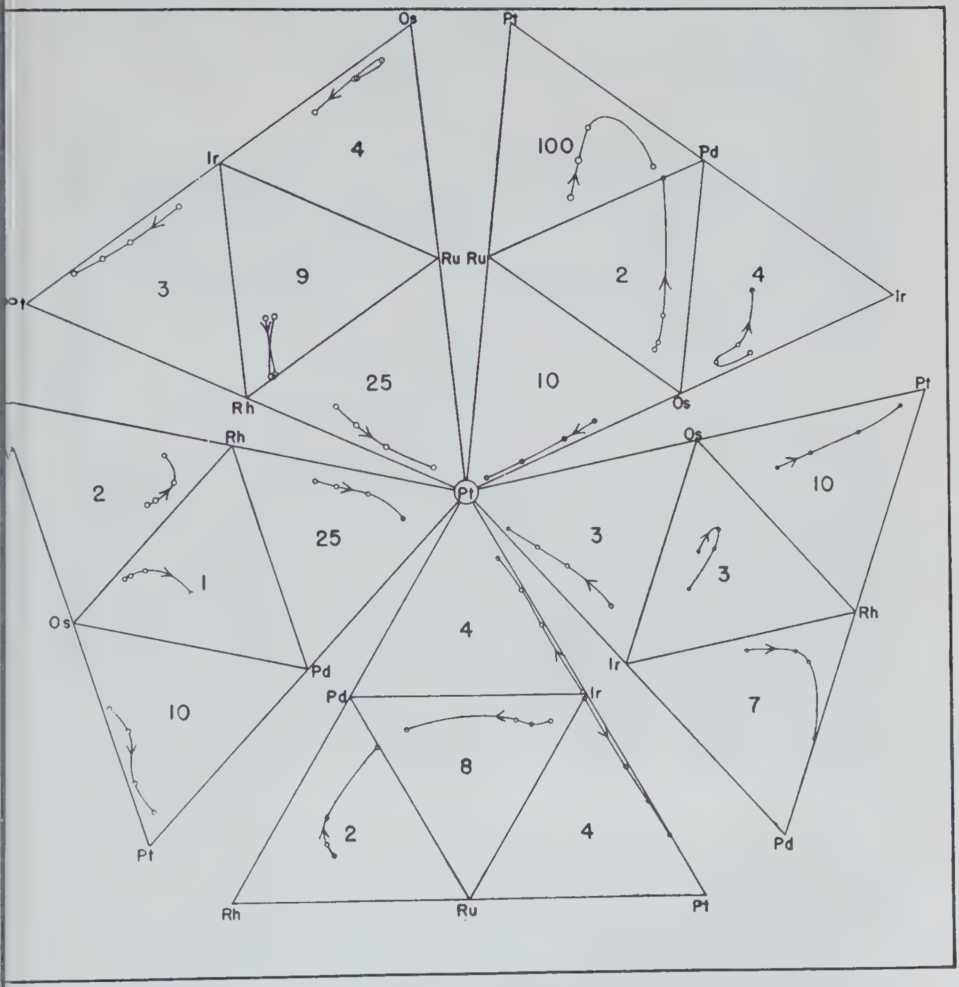
$$v = LMc$$

where c is the numerical value of either of the minor coordinates, and v is the required value of a minor coordinate in the magnified scale.

Magnification of scale is commonly necessary. Each trigon, however, is a separate and distinct unit, so that the methods of trilinear analytical

PLATINUM ANALYSES AND RECOMPUTED TRIADS

Platinum Creek and Fox Gulch																					
Platinum	70.23	71.90	75.03	73.99	75.12	93.58	91.97	93.72	97.15	99.10	97.31										
Iridium	23.00	23.55	24.57	24.23	24.60							82.68	78.96	83.02	91.79	97.32	92.20				
Osmium	4.45	4.55				5.92	5.82	5.93				15.98	15.26	16.04				68.35	87.53	69.56	
Ruthenium	.37		.40			.50			.52	.53		1.34			1.49	1.58		5.74	7.35		16.10
Rhodium	1.69			1.78			2.21		2.33		2.33		5.78		6.72		6.76	25.91		26.37	72.68
Palladium	.26				.28			.35		.37	.36			.94		1.10	1.04		5.12	4.07	11.22
Squirrel Creek																					
Platinum	78.93	80.69	83.63	82.50	83.61	95.15	93.69	95.13	97.68	99.25	97.66										
Iridium	15.16	15.49	16.06	15.84	16.06							79.03	74.02	78.93	89.00	96.21	88.88				
Osmium	3.73	3.82				4.50	4.43	4.50				19.47	18.24	19.45				66.60	86.21	66.33	
Ruthenium	.29		.31			.35			.36	.36		1.50			1.69	1.82		5.12	6.63		13.16
Rhodium	1.58			1.66			1.88		1.96		1.96		7.74		9.31		9.30	28.28		28.16	72.63
Palladium	.31				.33			.37		.39	.38			1.62		1.97	1.82		7.16	5.51	14.21
Salmon River																					
Platinum	84.76	86.26	88.11	87.16	87.94	97.25	96.10	97.04	98.39	99.38	98.18										
Iridium	11.27	11.47	11.71	11.59	11.69							82.45	76.63	81.35	89.06	95.50	87.78				
Osmium	2.23	2.27				2.55	2.53	2.55				16.29	15.14	16.07				61.66	80.75	58.66	
Ruthenium	.17		.18			.20			.20	.20		1.26			1.37	1.47		4.79	6.28		9.93
Rhodium	1.21			1.25			1.37		1.41		1.40		8.23		9.57		9.43	33.55		31.92	69.54
Palladium	.36				.37			.41		.42	.42			2.58		3.03	2.79		12.97	9.42	20.53
Clara Creek																					
Platinum	90.49	91.75	92.40	92.06	91.90	98.89	98.51	98.32	99.25	99.07	98.68										
Iridium	7.29	7.39	7.44	7.41	7.40							87.80	84.16	82.52	91.47	89.53	85.76				
Osmium	.85	.86				.93	.93	.93				10.27	9.84	9.65				55.65	50.00	41.32	
Ruthenium	.16		.16			.18			.18	.17		1.93			2.02	1.97		10.48	9.42		11.71
Rhodium	.52			.53			.56		.57		.57		6.00		6.51		6.10	33.87		25.15	37.84
Palladium	.69				.70			.75		.76	.75			7.83		8.50	8.14		40.58	33.53	50.45



PLATINUM METALS, GOODNEWS BAY DISTRICT, ALASKA

Fig. 7

geometry may be applied within trigons, but not from one trigon to another. Therefore no objection exists to showing different trigons at different scales; and where this is done, the magnification is given as a single large numeral within the trigon. Magnification of scale is impracticable where negative coordinates are utilized.

An example of the charting of 6 variables is shown in Fig. 7. For this purpose, four analyses of platinum metals, taken from a report by the writer[2] are used, each of which is a mean of a number of analyses. The four analyses are shown at the left of the subjoined tabulation, followed to the right by all possible triads recomputed to unity. All but one of the 20 trigons are used at magnified scales. Curves have been drawn through the charted points, to show the modes of variation; and arrows have been placed on the curves to show the relative positions of the four analyses.

Résumé

A method is shown for charting 5, 6, and 7 variables on the triangular faces of hypertetrahedra of 4, 5, and 6 dimensions. The triangles representing these faces are empirically arranged for the maximum conservation of space. The variables are computed into triads, each of which total unity, and are then charted in their respective trigons by the use of trilinear coordinates. Different scales are commonly required in the different trigons, and methods are given for producing such changes in scale. The charting of 6 variables is illustrated by the use of 4 analyses of platinum metals from the Goodnews Bay district, Alaska.

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[2] Mertie, J. B., Jr., The Goodnews platinum deposits, Alaska: *U. S. Geol. Survey, Bull.* **918**, 77–79 (1940).

THERMAL ANALYSIS OF QUARTZ AND ITS USE IN CALIBRATION IN THERMAL ANALYSIS STUDIES*

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Abstract

The character of the thermal analysis diagram of quartz is interpreted in terms of the latent heat of inversion from the low to high form of quartz and of the change in heat capacity (specific heat) accompanying the polymorphic transformation.

The sharpness of the thermal peak accompanying the inversion of quartz from the low to the high temperature form and its reproducibility make it an ideal means of calibrating thermal analysis apparatus.

The use of the inversion of quartz from the low to the high temperature form is here proposed as a fixed point for calibrating the temperature-thermocouple in thermal analysis apparatus. A series of thermal analysis diagrams are given in this paper for quartz of various grain sizes and of different paragenetic histories.

Apparatus

The differential thermal analysis apparatus in use in the Section of Geochemistry and Petrology of the U. S. Geological Survey is similar to the one developed by Hendricks and Nelson (1939) at the Department of Agriculture. This apparatus is of the dynamic type, that is, the temperature of the furnace and of the sample being studied is continuously changed. In this study the temperature was changed at the rate of 15° C. per minute. The temperature of the reaction chamber in the furnace is measured by means of a chromel: alumel thermocouple. The magnitude of the thermal effects such as inversion, dissociation or other reactions is measured by means of a platinum: platinum 90 per cent-rhodium 10 per cent differential thermocouple.

The reaction chamber is a nickel block containing three holes, two of which are of equal size and volume and adjacent to one another. These holes, or cells, are filled respectively with a thermally neutral substance, fused alumina, and the unknown sample to be tested. The two junctions of the differential thermocouple are centered in these cells. The third hole is perpendicular to the aforementioned cells and approximately between them. It is of smaller size. The hot-junction of the chromel:alumel thermocouple is inserted here.

The thermocouple used to measure the temperature of the reaction chamber was originally calibrated by the following indirect method. The deflection of a galvanometer is directly proportional to the electromotive force impressed across its terminals. The magnitude of the potential dif-

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ference developed by a chromel:alumel thermocouple as given by Roeser, Dahl and Gowens (1935) is 0.60 millivolts at 15° C. and 41.31 millivolts at 1,000° C. Accordingly, various potential differences ranging from 0.60 millivolts to 41.31 millivolts were impressed across the terminals of the galvanometer and the corresponding deflection of the galvanometer was recorded optically on photographic paper. A chart was then constructed relating the deflection of the galvanometer to the millivoltage across its terminals. The substitution of temperatures for the equivalent millivoltages of chromel:alumel thermocouples gives a deflection-temperature graph.

The above calibration assumes that all chromel:alumel thermocouples develop and reproduce the same potential difference at the same temperature. According to Roeser, Dahl and Gowens (1935) the manufacturers guarantee that these thermocouples will give values within the following limits, ±5° F. (3° C.) in the range 32° to 660° F. and to $\pm\frac{3}{4}$ per cent between 660° and 2,300° F. The thermocouples tested by Roeser, Dahl and Gowens fell within these limits. Within the limits of accuracy of routine thermal analysis, especially where the minerals are of the same type, the above assumptions are acceptable. In more precise work, or fcr those minerals which give off corrosive vapors, frequent calibration is necessary.

The direct method of using the inversion temperature of quartz as proposed here is simple, reproducible and requires no special electrical equipment as is used in the indirect calibration. Moreover, each thermocouple may be calibrated and recalibrated whenever desired.

The use of the inversion of quartz as a base point on the thermometric scale was advocated by Bates and Phelps (1927) of the National Bureau of Standards, who state on page 315:

> Specimens of quartz from sources widely distributed geographically were studied and the temperature at which the inversion starts on heating found to be identical (573.3° C.). This is found to be a fixed and definite temperature occurring with great sharpness and suitable for a new type of base point on the thermometric scale, as well as for the standardization and checking of thermocouples in the average physical laboratory.

The observations of many workers, using various techniques, agree in the constancy of the inversion temperature. A single observation on one sample, by Fenner (1913), gave a lower inversion temperature. This material is of questionable homogeneity and Fenner assumes that the low result is probably due to solid solution. This indicates that when clear quartz crystals, from localities known to yield pure specimens, are used there need be little concern over this anomalous result.

THERMAL ANALYSIS OF QUARTZ

Some typical quartz thermal analysis patterns are given in Fig. 1. Thermal-analysis curves show that up to the inversion point of quartz

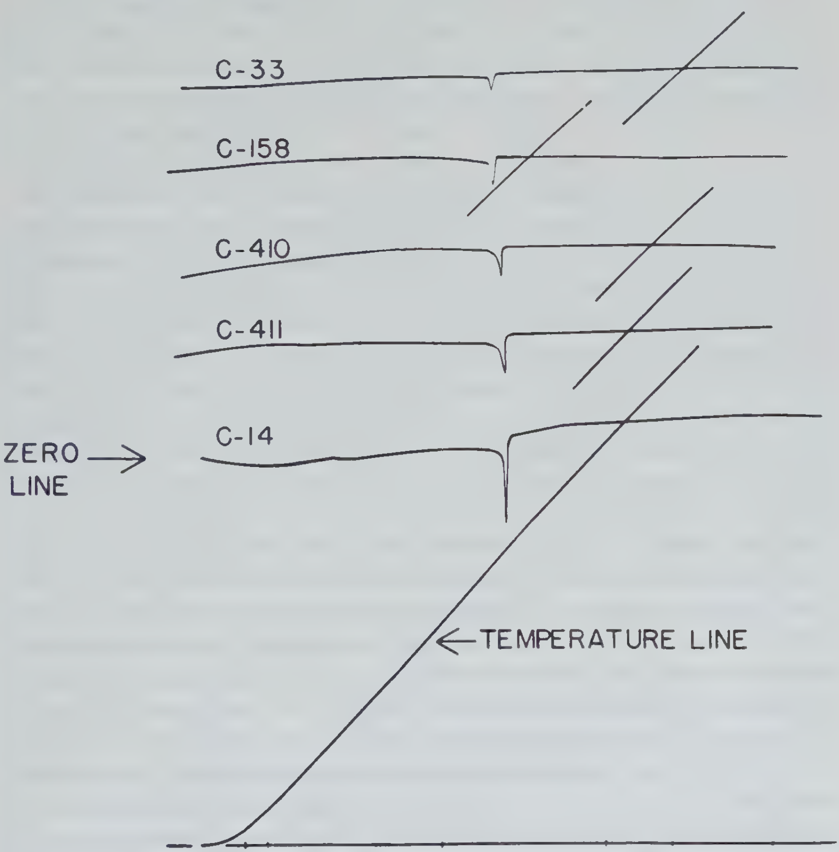

Fig. 1. Typical Thermal Analysis Curves of Quartz.

C-33	Quartz, var:—rock crystal, Hot Springs, Arkansas, 0.53 grams, −58 mesh, 600 ohms resistance with differential thermocouple.
C-158	Same as above, except sample weight 0.49 grams, 600 ohms resistance.
C-410	Quartz crystals, Valles Mountain, New Mexico. These crystals are pseudomorphs after high quartz. These crystals were taken through the high-low inversion three times before the curve was made. Sample weight 0.60 grams; crystals, 2 mm. in diameter, 600 ohms resistance.
C-411	Quartz, var:—novaculite powder, Hot Springs, Arkansas, 0.62 grams, −25 microns, 600 ohms resistance.
C-14	Quartz, var:—rock crystal, Hot Springs, Arkansas, −58 mesh, 150 ohms resistance with differential thermocouple.

the curve is essentially a straight line. After inversion is complete, the curve again becomes straight.

The height of the straight portion of the curve of high quartz is always displaced above that of low quartz. This is presumably caused by the change in the specific heat accompanying the inversion. Wietzel (1921) has measured the mean specific heat (mean heat capacity) at the inversion temperature 573° C. and found that the low modification has a mean heat capacity of 248.2×10^{-3} (in 20°-gram calories per degree centigrade) whereas the high modification of quartz has a mean heat capacity of 252.9×10^{-3}. These data were taken from Sosman's book (1927) and are values recomputed by Sosman from Wietzel's data. The difference in the mean specific heats (mean heat capacity) of the two forms of quartz is thus 4.7×10^{-3} (20°-gram calories per degree centigrade). Moser (1936) has determined the true specific heat, c_p, of quartz crystal from Brazil, and a graphical interpolation of his data indicates that the difference in true specific heat may be as much as 10×10^{-3}. Differences in the heat capacity of this magnitude produce the offset observed. After the galvanometer is deflected to the maximum, at the peak of the quartz inversion, it returns to the new "offset" zero without any overshooting. After the inversion is completed, the curve continues as a monotonous line.

The area under the curve is proportional to the heat effect accompanying the inversion of quartz. Gibson (1928) has determined the latent heat of the inversion to be 3.1 calories per gram. An attempt was made to correlate the area under the curve with the weight of the sample used in the reaction cell. Such measurements have been made for other substances and a proportionality relation between the area under the curve and the weight of the sample established. In this study, most of the thermal analysis curves were obtained using a resistance of 600 ohms in the differential thermocouple circuit. At this sensitivity the area under the curve is small and is approximately 0.18 square centimeters for a half gram sample of quartz. With such a small area, the error introduced by choosing the proper base line to close the loop is so large that a correlation between area under the curve and weight of sample could not be established by means of a number of trial measurements with a polar planimeter. An angular measurement such as that suggested by Dean (1947) gave no better agreement. Berkelhamer (1944) using a resistance of 50 ohms in the differential thermocouple circuit produced larger areas from which he obtained a "partial area under the curve" versus "weight of sample" relationship. His partial area represents about 30%± of the total area.

CONSTANCY OF THE THERMAL CURVES OF QUARTZ

In order to detect any variation in the character of the thermal curves of quartz two variables (grain size and thermal history) were studied.

Thermal analyses were made on samples of fairly uniform grain size and on heterogeneous mixtures. The maximum size tested was a sample of quartz crystals all of which measured about two millimeters in diameter, and the minimum size was a natural novaculite powder whose grain size was 25 microns and less. The heterogeneous mixtures of grains were prepared by grinding rock crystal to pass a 58-mesh cloth sieve. These samples all produced curves whose shape and character are fundamentally identical (see Fig. 1).

The effect of previous thermal history was investigated by analyzing specimens of different paragenetic histories and by successively running the same sample through several inversion cycles. Quartz crystals of low-temperature hydrothermal origin, low quartz paramorphs after high quartz, and novaculite gave the same pattern. Likewise, the low quartz paramorph after high quartz from Valles Mountain, New Mexico, was rerun four successive times and no significant variation was noted in the curves. Our experience with the thermal-analysis apparatus conforms with that of other investigators using different methods of studying the inversion of quartz.

Method of Calibrating the Thermal Analysis Apparatus

The establishment of a base line is necessary for temperature measurement and a system commonly used with photographic recorders is to expose the sensitive paper to the direct undeviated light beams from the galvanometer mirrors. In the "drum type" camera exposures are made at four or five positions along the circumference. A line drawn through the points, so located, establishes the base line.

To illustrate the technique of calibration, a thermal record of a quartz-gibbsite mixture is used (Fig. 2). A line is drawn perpendicular to the base line and passing through the peak of the quartz inversion. The segment of the line *AB* is measured. Its endpoints *A* and *B* represent the position of the galvanometer beam at room temperature and at the inversion temperature of quartz, 573° C., respectively. It is necessary, therefore, to correct the measurement made above for the "cold-junction error."

The corrected measurement on the original record of Fig. 2 is 13.35 cms. This value divided into the temperature of the inversion, 573° C., yields the constant 42.95. This constant represents the value in degrees centigrade of one centimeter along the line perpendicular to the base line. Its use is illustrated in the determination of the decomposition temperature of gibbsite. A straight line is drawn perpendicular to the base line and passing through the gibbsite peak. The distance *DE* is measured and to it is added the correction for room temperature giving 7.35 cms. This value multiplied by the factor given above, 42.95, gives 315° C. as the indicated temperature.

Although the relation between millivoltage and deflection of the galanometer is a true proportionality, this is not true for the relation between temperature and deflection of the galvanometer. This lack of proportionality arises from the characteristics of the chromel: alumel thermocouple. For this thermocouple equal differences in millivoltage throughout the range of zero to 41.31 millivolts do not correspond to equal differences in temperature. To correct the indicated temperature for this difference a correction curve with its zero at 573° C., the inversion temperature of quartz, was constructed (Fig. 3). Using the millivoltage corresponding to

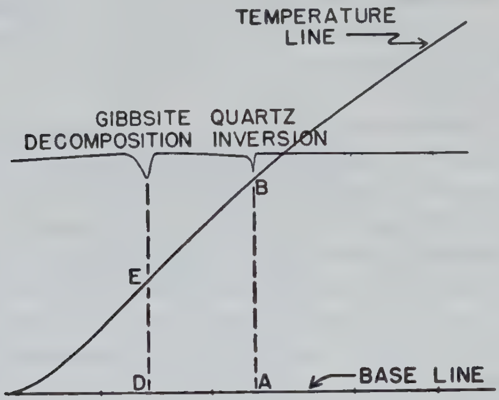

FIG. 2. Thermal analysis record of a mixture of 95% quartz and 5% gibbsite showing method of determining the temperature of the gibbsite dissociation.

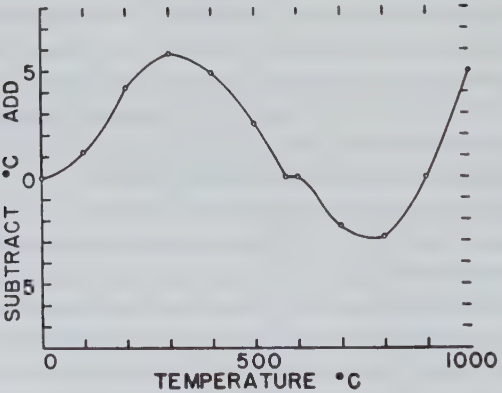

FIG. 3. Correction curve for temperatures observed with chromel: alumel thermocouple using quartz inversion temperature 573° C. as base point.

573° C. as the base, a true proportionality millivoltage for equal steps in temperature (100° C.) was calculated. The difference between the calculated millivoltage and the actual millivoltage gives the correction at a given temperature. The correction at 315° C. is thus 5.8° C. giving 321° C. as the temperature of the gibbsite decomposition for this particular sample.

Calibration at two additional points would be desirable for very accurate thermometry, but for most work in thermal analysis this is not required. A check on the sufficiency of the correction curve (Fig. 3) was afforded by an accidental recording of the heat effect accompanying the magnetic transition in nickel. Using the correction indicated by Fig. 3, the temperature of the transition is 353° C. which agrees very well with the accepted value of 354° C. ± 1° C. found by Moser (1936).

Observations on the Calibration of the Thermocouples

A selection of the data of twelve representative calibrations using quartz for the two chromel:alumel thermocouples used in the same thermal-analysis apparatus over a period of two and one-half years is given in Table 1. During this period the two thermocouples frequently became corroded at the hot junction and had to have new junctions welded together. The replacement of the old junction by a new junction always changes the value of the factor and this accounts for the difference between the runs C-410 and C-411.

The factors vary from a minimum of 40.72 to a maximum of 42.57 which represents a difference of 1.8° C. per centimeter. In Table 2, the temperature is computed for several positions on the record using the factor derived by direct calibration of the galvanometer, and the minimum and maximum values derived by calibration with quartz. The values in the table show that the difference between the selected factors increases as the temperature increases.

A study of Tables 1 and 2 shows that no great reliance can be placed on the value of the temperatures computed from the factor derived by the direct calibration of the galvanometer. Moreover, the value of the factors obtained by calibration with quartz shows that the factors change with continuous use of the thermocouple and whenever a corroded head is replaced. These results show that it is advisable to calibrate with quartz at frequent intervals. Mixtures containing quartz as a component when analyzed furnish a direct check on the calibration provided the quartz does not enter into a reaction with the other components. Since the rate of heating is so rapid, quartz rarely reacts, if at all, below 573° C.

One finds statements in the literature concerning the variation of the temperature of the peak in a nonreversible reaction and this has been

Table 1. Calibration Data for the Temperature Thermocouples

Number of Run	Weight of Sample	Factor ° C./cm.	Resistance in series with thermocouple	Distance between base line and temperature curve	Locality
C-14		40.93	150 ohms.	14.00 cm.	Quartz-variety: rock crystal, Hot Springs, Arkansas.
C-26	0.5218 gms.	40.72	150	14.07	Same as above.
C-33	0.5329	41.67	600	13.75	Same as above.
C-60	0.5291	40.92	600	14.05	Same as above.
C-158	0.4917	40.78	600	14.10	Same as above.
C-292	0.6589	41.88	600	13.68	Same as above.
C-296	0.7528	41.67	600	13.75	Same as above.
C-320		41.10	600	13.95	Same as above.
C-401	0.6122	42.57	600	13.46	Same as above, a re-run of C-400.
C-408	0.6031	42.38	600	13.52	Quartz crystals, Valles Mountain, New Mexico, a re-run of C-407.
C-410	0.6031	42.13	600	13.60	Same as above, a re-run of C-407, 408, 409.
C-411	0.6171	41.67	600	13.75	Natural novaculite powder, Hot Springs, Arkansas.
Direct calibration of galvanometer		40.32			

Table 2. A Comparison of Temperatures Calculated from the Various Factors

Distance	Factor obtained by Direct Calibration of galvanometer = Fg = 40.32° C./cm.	Factors obtained by calibration with quartz: Lowest $Fq_1 = 40.72$	Factors obtained by calibration with quartz: Highest $Fq_2 = 42.57$	Difference $Fq_2 - Fg$	Difference $Fq_2 - Fq_1$
5 cm.	202° C.	204° C.	213° C.	11° C.	9° C.
10	403	408	426	23	18
15	605	612	639	34	27
20	806	816	852	46	36
22	887	897	937	50	40

attributed to grain size, the presence of other materials, and rate of heating. It appears from this study that the variation in peak temperature may also arise from poor thermometry. If the variation in the peak temperature of a given reaction is studied it will be necessary to calibrate the temperature thermocouple. If the calibration is made in the nickel reaction block, only reversible processes such as the inversion of quartz should be used.

ACKNOWLEDGMENT

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IMMERSION MEDIA CONTAINING METHYLENE IODIDE

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ABSTRACT

The usefulness of methylene iodide as a constituent of immersion media is emphasized. The non-linear relationship of indices of refraction to composition by volume of some liquids containing methylene iodide is shown by experimental data.

An empirical equation has been devised for the calculation of indices of mixtures of methylene iodide and 1-bromonaphthalene from volume percentage data. Calculated indices show close agreement with experimental values.

The decomposition, purification, and preservation of methylene iodide is discussed.

Since 1886, when proposed by R. Brauns (1), methylene iodide, CH_2I_2, has been widely used as an immersion medium and as a constituent of immersion media prepared by mixing this substance with other liquids and solids. It is almost invariably used as a component of liquids whose indices of refraction are above 1.66 and has been recommended by Schroeder van der Kolk (2), F. E. Wright (3), Larsen and Berman (4), and others. Other organic derivatives (such as phenyldiiodoarsine (5), phenyl sulfide and mercury methyl (6)) have been proposed for the preparation of index liquids in upper ranges but the most popular material has probably been methylene iodide. Recently the usefulness of this compound has been emphasized by C. D. West (7) who has proposed a series of liquids composed of phosphorus, sulfur and methylene iodide to cover the range of indices from 1.74 to 2.06. According to Brunn and Barth (8), the stability of these media in storage leaves little to be desired.

Methylene iodide, despite its usefulness and popularity, has certain recognized disadvantages. It is expensive, is decomposed by light and heat, has relatively high dispersion and a larger temperature coefficient of refraction than liquids of lower refractive index. To the research worker who prepares his own liquids, perhaps the most annoying disadvantage of this substance is the departure of its mixtures from behavior as ideal solutions. It has been found that the properties of the commonly used mixtures of methylene iodide and other substances such as 1-bromonaphthalene are not straight-line functions of composition. This has been pointed out by Mayrhofer (9) in a recent paper on immersion liquids. Composition-refractive index data which have been gathered during the preparation of a series of immersion media containing methylene iodide are presented below.

PREPARATION OF LIQUIDS IN THE RANGE $n=1.66$ TO $n=1.74$

The primary liquids used to prepare immersion media in this range were 1-bromonaphthalene and methylene iodide. Some workers have considered 1-chloronaphthalene as a desirable alternative for 1-bromonaphthalene but the author's work has shown that the employment of the latter can effect economy in the use of methylene iodide and reduce the total cost of a set of liquids. Further, impure 1-chloronaphthalene or "Halowax oil" is considered by Butler (10) to be undesirable for use in immersion liquids because it deposits gummy material which collects on the containers.

Buerger (11) has discussed the optical properties of ideal solutions and pointed out that the indices of refraction of liquids which form ideal solutions are linear functions of composition. However, Kaiser and Parrish (12) have presented data and mixing curves for methylene iodide and 1-chloronaphthalene proving that these liquids do not form ideal solutions. The data of Mayrhofer (9) and of the author show that methylene iodide and 1-bromonaphthalene also form solutions which are not ideal, and this is to be expected since the two naphthalene derivatives are quite similar.

Since mixtures containing methylene iodide have indices of refraction which are not linearly related to composition by volume, a simple formula for the composition of such liquids as presented by Schroeder van der Kolk (2), Buerger (11), or Rogers and Kerr (13) cannot be used for their preparation. However, the composition of such liquids may be calculated by means of an equation of higher degree as shown by Mayrhofer and Wratschko (14). In a recent paper in an obscure publication, these authors have presented an empirical equation which fits their experimental data with considerable accuracy. The equation is of the form:

$$y = A_0 + A_1x + A_2x^2 + \cdots + A_nx^n. \qquad (1)$$

The empirical equation given is:

$$n_{20} = 1.658 + \frac{1}{10^7}(4000x + 43x^2) \qquad (2)$$

in which x is the volume per cent of methylene iodide and n_{20} is the index of refraction of mixtures of 1-bromonaphthalene and methylene iodide in Na light at 20° C.

Re-evaluation of the empirical coefficients gives the following equation which shows better agreement with the author's experimental data:

$$n_{20} = 1.6587 + \frac{1}{10^7}(4530x + 37x^2). \qquad (3)$$

Calculated values of n_D are given in Table 3 together with observed experimental values. Differences between observed and calculated indices are of the same order as those found by Mayrhofer and Wratschko.

The calculation of percentage composition of liquids of desired indices using equation (3) is rather laborious. Therefore, a mixing curve or composition-refractive index curve prepared from experimental data will enable liquids of intermediate indices to be prepared quickly.

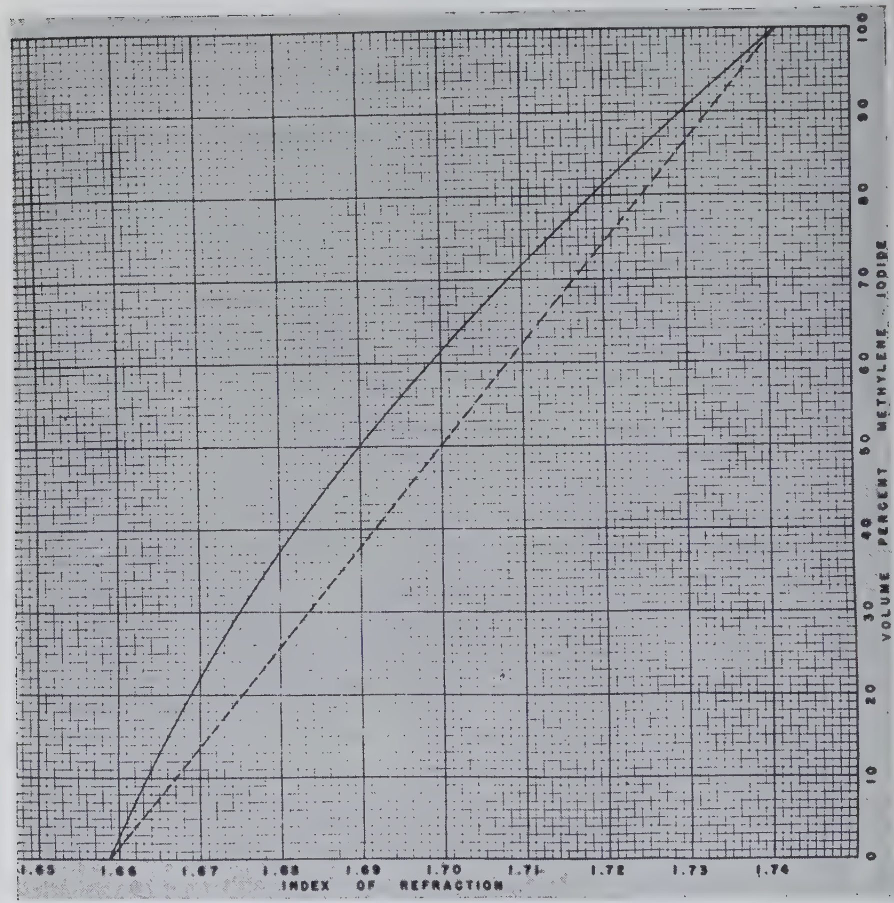

FIG. 1. Composition-refractive index curve for mixtures of methylene iodide and 1-bromo-naphthalene in Na light at 20° C. The solid curve is the graph of experimental data. The dashed straight line represents properties of a hypothetical ideal solution series.

Since some batches of chemicals used for the preparation of immersion media vary slightly in index of refraction, it is recommended that composition curves be prepared by each worker who undertakes the preparation of his own media.

The curves may be prepared easily by plotting composition against refractive index as shown in Fig. 1. A straight line representing the properties of ideal solutions may be drawn between points indicating the indices of the pure primary liquids. (Dashed line, Fig. 1.) Trial mixtures containing convenient volume percentages of the primary liquids should be prepared, thoroughly mixed, and the indices of refraction measured (Table 1). For purposes of comparison to determine the deviation of mixtures from ideal behavior, the volume percentages of trial liquids may be obtained from the straight line graph. When the indices are plotted against composition and a smooth curve drawn through these points and the values for the pure liquids, a curve results which is used to determine the composition of liquids with desired indices of refraction (Table 2). The accuracy of the method is determined by the accuracy of graphical interpretation and precautions taken in measuring the liquids.

The data for Fig. 1 which are tabulated in Tables 1 and 2 were obtained by using 10 ml. burettes which were graduated in 0.05 ml. Readings were estimated to 0.01 ml. Volumes of individual mixtures prepared were 10 ml. The liquids used were fresh stock chemicals obtained from the Eastman Kodak Company, Rochester, New York. The indices of refraction for Na light ($\lambda = 5893$ Å.) were measured on a one-circle goniometer by the method of minimum deviation, using a prism provided with circulating water for temperature control, similar to that described by Butler (10).

Although it has been suggested that each worker prepare his own composition curve, it is believed that direct use of the data recorded here may be made if primary liquids are available which have the same constants as the media employed by the author.

Experimental mixtures which have been prepared to determine the composition curve will, in general, not have indices which conveniently fit into a set having regular intervals of, say, 0.01 or 0.005 (see Table 1). These liquids may be adjusted to a desired index by adding an amount of one constituent determined by a simple calculation as shown in the example below:

Composition of 10 ml. sample of experimental liquid, $n = 1.7134$
$10.0 \times 0.750 = 7{,}50$ ml. CH_2I_2
$10.0 \times 0.250 = 2.50$ ml. $C_{10}H_7Br$

Composition of liquid, $n = 1.710$ (From curve, Fig. 1)
71.7% CH_2I_2
28.3% $C_{10}H_7Br$

Hence

$0.717\ V_a = 7.50$ ml. CH_2I_2 present in original liquid.

$V_a = 10.46$ ml. total volume of adjusted liquid.

$0.283\ V_a = 2.96$ ml. $C_{10}H_7Br$ present in adjusted liquid.

Therefore

$2.96 - 2.50 = 0.46$ ml. of $C_{10}H_7Br$ must be added to the original liquid to bring n to 1.710.

It is assumed in making these calculations that the initial volume of the mixed liquids remains constant and that the solutions are ideal. These assumptions are approximately true if minute drops of liquid are used in determining the indices of initial mixtures and if adjustments are relatively small. The method is superior to adjustment by trial and error.

PURIFICATION AND PRESERVATION OF METHYLENE IODIDE

Methylene iodide is unstable when exposed to light and heat and unless precautions are taken it has a tendency to liberate iodine. The following hypothetical equation may be written to express the decomposition:

$$\underset{\text{Methylene iodide}}{6CH_2I_2} \rightarrow \underset{\text{Methyl iodide}}{CH_3I} + \underset{\text{Iodoform}}{3CHI_3} + \underset{\text{Iodine}}{I_2} + \underset{\text{Ethane}}{C_2H_6}$$

Emschwiller (15) has studied the photolysis of methylene iodide and related compounds, but further work is required to demonstrate the true nature of the decomposition with which we are concerned here.

The coloration or opacity which results from the presence of free iodine is undesirable in an immersion liquid. Reinhard Brauns (1), in the original article describing the use of methylene iodide, stated that this substance might be purified by shaking with an aqueous solution of potassium hydroxide. Later authors have mentioned this procedure in connection with the use of methylene iodide as a heavy liquid (G. = 3.3) for mineral separations, but this method of purification has evidently been missed by some who are interested in methylene iodide as an immersion medium.

Schroeder van der Kolk (16) has advised the use of copper to prevent discoloration of methylene iodide and in the writer's opinion this procedure is most satisfactory. However, copper is slow to decolorize methylene iodide; therefore, it is suggested that deeply discolored samples of this substance be shaken with dilute potassium hydroxide solution until the original pale color is restored. The liquid should then be washed with distilled water, dried over anhydrous calcium chloride and filtered. It may then be preserved over clean copper wire or foil which has been previously treated with hydrochloric acid to remove oxidation products

TABLE 1

Index of Refraction, n_D	Vol. % CH_2I_2	Vol. % $C_{10}H_7Br$	Temperature ° C.
1.6587	0.0	100.0	19.7
1.6723	25.0	75.0	20.0
1.6909	50.0	50.0	20.0
1.7134	75.0	25.0	20.0
1.7410	100.0	0.0	19.9

TABLE 2

Index of Refraction, n_D	Vol. % CH_2I_2	Vol. % $C_{10}H_7Br$	Temperature ° C.
1.6606	2.7	97.3	18.3
1.6705	21.3	78.7	18.3
1.6800	36.2	63.8	18.4
1.6893	48.8	51.2	18.5
1.7001	60.3	39.7	18.3
1.7102	70.7	29.3	18.5
1.7202	80.6	19.4	18.4
1.7302	90.0	10.0	18.2
1.7402	99.1	0.9	18.3

TABLE 3

1 Calculated Index of Refraction (Equation 3)	2 Observed Index of Refraction (See Table 2)	3 Index of Refraction (Corrected to 20° C.)	4 Difference (Column 1 and 3)
1.6599	1.6606	1.6598	.0001
1.6700	1.6705	1.6696	.0004
1.6800	1.6800	1.6791	.0009
1.6896	1.6893	1.6884	.0012
1.6995	1.7001	1.6991	.0004
1.7092	1.7102	1.7092	.0000
1.7192	1.7202	1.7191	.0001
1.7294	1.7302	1.7290	.0004
1.7399	1.7402	1.7390	.0009

or tarnish. If the copper is renewed occasionally, the discoloration of the methylene iodide will be avoided.

The use of tin and mercury advocated by some is not recommended.

J. W. Retgers (17) has shown that stannic iodide is soluble in methylene iodide and qualitative tests by the writer have shown the presence of mercury in a filtered sample of methylene iodide which previously had stood over this metal.

ACKNOWLEDGEMENTS

The writer is indebted to Dr. C. Osborne Hutton for valuable suggestions and criticism during the preparation of this paper, to Dr. A. C. Waters for encouragement to publish these data, and to Dr. A. F. Rogers for suggestions which led to this work.

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ALIGNMENT CHART FOR CALCULATION OF SPECIFIC GRAVITY

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ABSTRACT

An alignment chart is presented in the form of three scales arranged along the lines of a "Z" which solves the equation for determination of the specific gravity of a substance in terms of its weight in air and its weight when submerged in water. The construction of the chart is easy for any range of weights. If constructed on 8×10-inch paper, readings may be made to better than ±1%. A larger chart would permit proportionately better accuracy.

INTRODUCTION

With a few notable exceptions, geologists and mineralogists have made little use of nomographic methods, and almost no use of the particular device known as the alignment chart. An alignment chart consists of three or more scales constructed along straight or curved lines and related to one another in such a way that any straight line drawn across them (called an index line) will intersect the scales at points that correspond to a solution of the equation represented. Textbooks describing many types of alignment charts may be found in most engineering libraries.[1]

The necessity for repeated solution of the well known formula for determining specific gravity in terms of the weight of a substance in air, divided by the difference between its weight in air and its weight in water, led the writer to construct a "Z" alignment chart for the purpose. The formula is as follows:

$$d = W_a/[W_a - W_w], \tag{1}$$

where d = density or specific gravity, W_a = weight in air, W_w = weight when submerged in water. This fits the type equation for the "Z" chart, which may be given as follows:[2]

$$af_3(w) = f_1(u)/[f_1(u) + bf_2(v)]. \tag{2}$$

Setting $a=1$, $f_3(w)=d$, $f_1(u)=W_a$, $b=-1$, and $f_2(v)=W_w$, we obtain exact correspondence between (1) and (2).

THE CHART

For the problem at hand, the two parallel scales of the "Z" represent the two observed weights W_a and W_w. They have uniform spacing and equal moduli, i.e., equal distances represent equal increments of weight.

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[1] Two recently published books on charts and scales are C. O. Mackey, *Graphical Solutions*, New York, 1944; and A. S. Levens, *Nomography*, New York, 1948.

[2] Mackey, *op. cit.*, p. 68.

Graph paper with millimeter divisions, or with 20 divisions per inch, is readily available; a sheet 8.5×11 inches in over-all dimensions serves to construct a chart that will give satisfactory accuracy for many purposes.

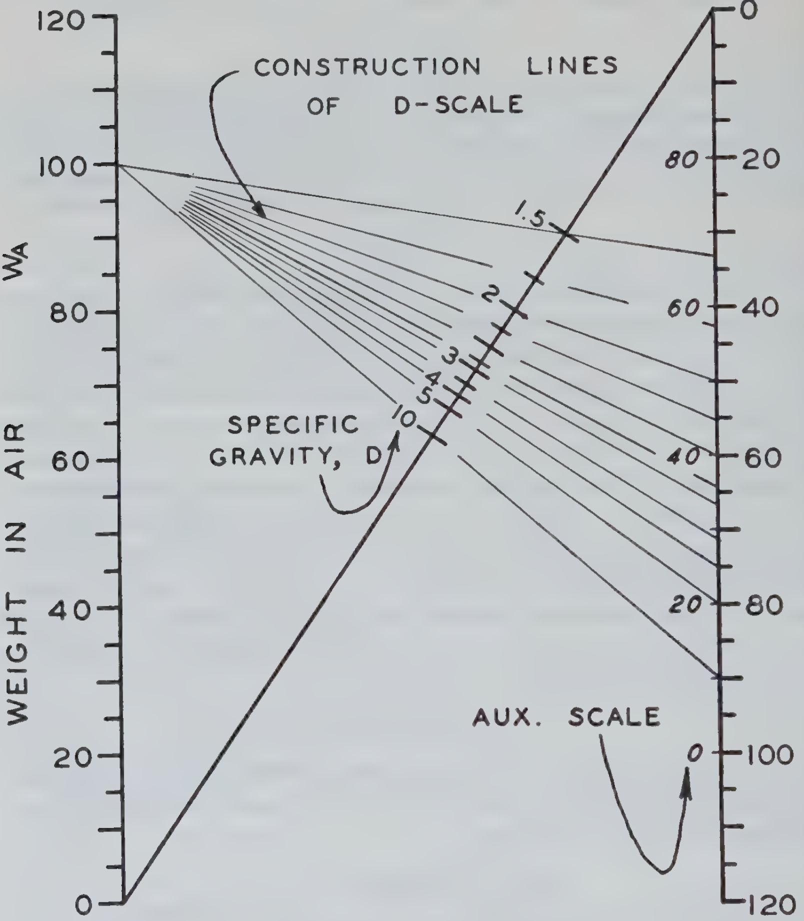

FIG. 1. Layout and construction of alignment chart for determination of specific gravity. Construction lines from point M on W_A scale to M/D on auxiliary scale.

A larger sheet will give proportionately greater accuracy. Along opposite edges of the ruled paper, lay off the scales for W_a and W_w, starting at diagonally opposite corners as in Fig. 1 and using any convenient scale modulus (e.g., 1 inch = 10 weight units) for both scales. The scale modulus may be chosen as to cover any range desired, or the scales may be numbered so as to show more than one range. The unit of weight (milligram, gram, pound, etc.) is immaterial provided that the same unit is used for both weighings.

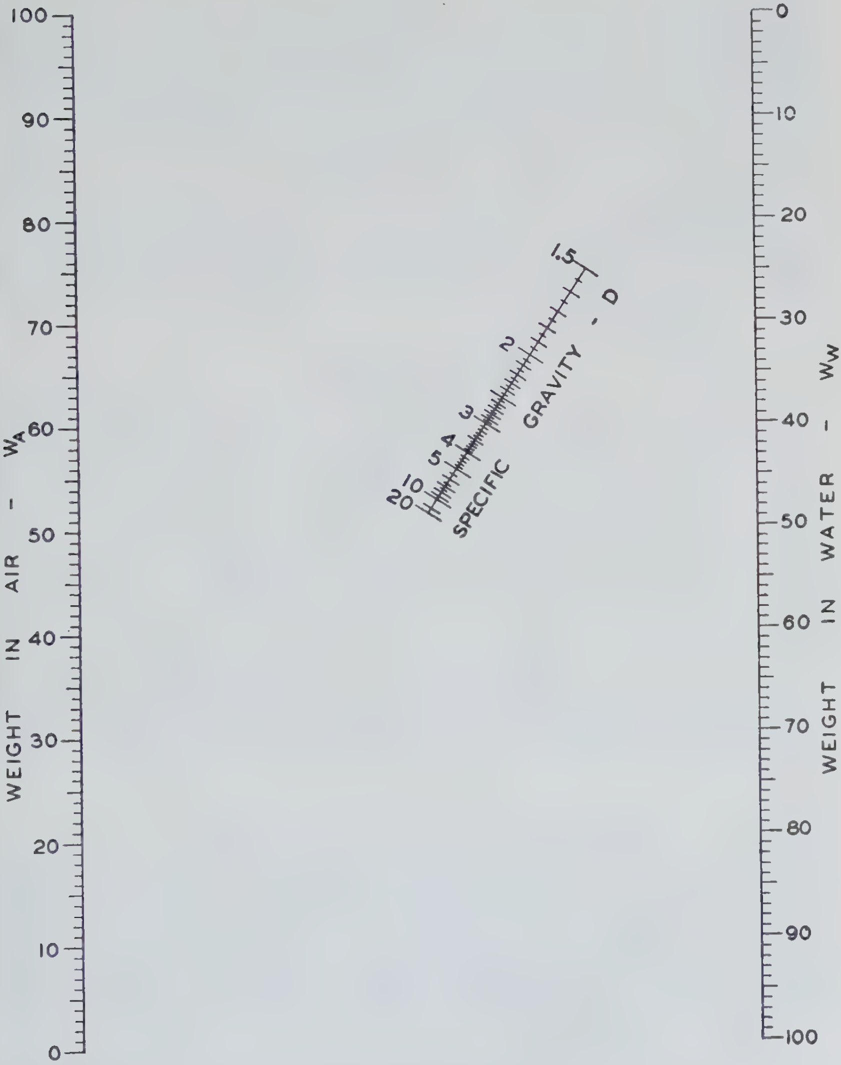

FIG. 2. Alignment chart for determination of specific gravity $D=W_A/[W_A=W_W]$

Note: *A straight index line from* W_A *to* W_W *cuts diagonal scale at* D.

The diagonal scale is calibrated by a simple graphical method. Assuming some constant value, say 100, for W_a, equation (1) is rearranged as follows:

$$100 - W_w = 100/d. \tag{3}$$

Equation (3) gives the clue to the calibration of the diagonal scale, for by laying off in pencil an auxiliary scale $(100 - W_w)$ along the W_w axis, as shown in Fig. 1, any desired point on the diagonal scale may be found by drawing a line from 100 on the W_a scale to 100/d on the auxiliary scale. Tables of reciprocals are included in many books containing mathematical tables,[3] and should be used for convenience and accuracy in evaluating the quantity 100/d which is found on the auxiliary scale. Figure 1 shows the steps in the layout of the whole chart, especially detailing the procedure for the diagonal scale. A small copy of the completed chart is shown in Fig. 2.

Use of the Chart

The "Z" chart is very simple to use. The observational data are W_a, the weight of a sample in air, and W_w, its weight when submerged in water. To calculate specific gravity the larger of these numbers is divided by their difference; but the subtraction and division are simultaneously performed by the chart (Fig. 2). A straight-edge is laid from the observed value W_a on the left scale to the observed value of W_w on the right scale; this intersects the diagonal d-scale at the proper value for the specific gravity with reference to the liquid used (water). For example, suppose that a specimen weighs 30.0 grams in air and 20.0 grams in water. One can mentally divide the larger (30.0), by the difference (10.0) obtaining a specific gravity of 3.00: note that a ruler laid across the chart from $W_a = 30.0$ to $W_w = 20.0$ intersects the d-scale at 3.00.

Modification for Use with Toluene

A factor that has not been mentioned so far is the density of the water or other liquid used in the submerged weighing. The density of water does not vary enough to affect results more than about 0.3% in the extreme range of room temperatures. This is below the limit of accuracy of the d-scale if the chart is constructed on paper of notebook size, and can therefore be ignored.

However, when toluene or other liquid is used instead of water, the density of the liquid must be used as a multiplier to correct the apparent specific gravity with reference to the liquid, to the true specific gravity with reference to water. Two alternatives are presented. First, the diagonal d-scale may be recalibrated for a new, constant value of the density of the liquid to be used. (There is room on the chart for this to be done once without confusion, since only the upper half of the diagonal axis has been used: to use the lower half, interchange the designations W_a and W_w on the parallel scales and calibrate the lower half of the diagonal axis for the new density.) An error of less than 0.5% will be introduced if toluene is the liquid used and a standard temperature of 24° C. assumed, since

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[3] *Handbook of Chemistry and Physics*, Chemical Rubber Publishing Co., Cleveland, Ohio, any edition; also many other similar handbooks.

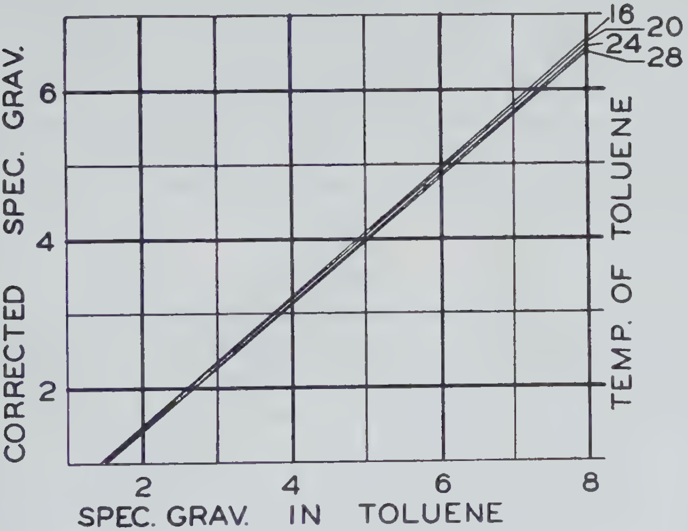

FIG. 3. Intersection chart of $D = _{tol.}\ k_T D_{tol.}$ where k_T=correction factor depending upon temperature and $D_{tol.}$ is specific gravity with respect to toluene.

the range of densities of toluene from 20° to 30° is about .0067 and the density of toluene is 0.86 at room temperatures of 23° or 24°. This maximum error due to temperature variation may be too great for some purposes, but is not excessive for many uses, and is near the maximum error to be expected for "Z"-chart constructed on paper of note-book size. A larger chart, as stated above, would improve the accuracy of chart readings in direct proportion to the size of the chart, and would necessitate making allowance for temperature separately.

A second alternative, necessary if several liquid densities are to be considered (i.e., several liquids, or several temperatures in one liquid), is to make the density-of-liquid correction separately after first determining the specific gravity with respect to the liquid and noting the temperature. Since this correction involves only a multiplication, it can be done by slide rule or it can be done with an auxiliary chart consisting of a graph made up with uncorrected specific gravities along the abscissa axis, corrected specific gravities along the ordinate axis, and a family of straight lines through the origin for the several densities of liquid desired. Figure 3 illustrates the plan of such an auxiliary chart, for correction of observed specific gravities in toluene at various temperatures. In actual use, a larger one should of course be made. The closeness of the diagonal lines illustrates clearly the smallness of the error inherent in assuming a constant density of toluene. The uncorrected value of specific gravity derived from readings using toluene instead of water is obtained from the "Z"-chart; this value is found on the abscissa scale of a chart like Fig. 3, and followed upward to the appropriate temperature line; thence horizontally to the left to the correct value of specific gravity on the ordinate scale. Figure 3 may be designed for use in connection with the basic "Z"-chart for water, or with the modification described in the preceding paragraph.

Discussion

The accuracy of the chart method in general is dependent mainly upon the size of the chart used. Accuracy of reading charts varies in different parts depending upon the angle of intersection of two lines; in the present chart the acuteness of the angle between the straight edge and the diagonal scale is indeed a limitation of the accuracy with which the reading can be made: but data which produce such an acute angle are in general the very data that cannot give reliable answers. Thus, if the specimen weighs only 10 milligrams, and its weight in liquid is 7.04 milligrams, the acuteness of the angle is such that a reading of the density may be anywhere from 3.4 to 3.5 on the diagonal scale. This serves immediately to warn that the data, though possibly more accurate than this result seems to indicate, must still be used with great caution. Since the two parallel scales are not calibrated for any particular weight units, the results of both weighings may be multiplied by 2 or 10 or any other number, and the resulting figures used with the chart, thereby improving the accuracy of the computation by making the index line intersect the diagonal scale at a larger angle. On the other hand, if the weight in air is 40.0 milligrams and in liquid is 36.0 milligrams, the index line crosses the diagonal scale at a large angle and the resulting determination of $d = 10.0 \pm 0.3$ is probably as accurate as the data warrant. The diagonal scale is compressed in this vicinity, reflecting the fact that the *difference* (small in this example) between the observed weights enters the denominator of the formula; its relative accuracy limits the resulting accuracy of the quotient severely. This factor is much less serious with substances of lower density, and for them the diagonal scale is accordingly more extended.

At the scale of reproduction, it is not intended that the "Z"-chart be of much practical use except perhaps to give an approximate result for checking the order of magnitude of the results obtained by other means. On a sheet of graph paper 7.5×10 inches, accuracy of about ±.01 may be obtained in the density range from 2.0 to 3.0, ±.02 from 3.0 to 4.0, and ±.05 from 4.0 to 5.0. If the length of the diagonal scale of the chart is doubled, the accuracy is improved proportionately.

OPTICAL PROPERTIES OF GLASS FROM ALAMOGORDO, NEW MEXICO*

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Abstract

The explosion of the atomic bomb at Alamogordo, New Mexico, fused the immediate surface of the arkosic sands of the area. This produced two distinct types of glass, one derived from the feldspar clay fraction of the sands, and the other direct fusion of the quartz to silica glass. The properties and relations of these materials are described in detail.

Specimens of glass resulting from the explosion of the experimental atomic bomb at Alamogordo, New Mexico, have, by various means, come into the hands of numerous institutions and collectors. Notwithstanding this availability, no studies of the material have been published, although a mere description of its physical character would have no bearing on atomic problems. Samples of the glass were collected by C. A. Anderson of the Geological Survey with the permission of Major General Leslie R. Groves, Commanding General for the Manhattan District. The results of a brief study of this glass, made in the laboratories of the U. S. Geological Survey, will no doubt be of interest to mineralogists and petrologists.

The glass, in general, formed a layer 1 to 2 centimeters thick, with the upper surface marked by a very thin sprinkling of dust which fell upon it while it was still molten. At the bottom is a thicker film of partly fused material, which grades into the soil from which it was derived. The color of the glass is a pale bottle green, and the material is extremely vesicular, with the size of the bubbles ranging to nearly the full thickness of the specimen. Figure 1 shows photomicrographs of typical specimens of the Alamogordo glass.

The material from which the Alamogordo glass was derived was an arkosic sand composed of angular quartz grains, abundant feldspar including both microcline and smaller amounts of plagioclase, together with small amounts of calcite, hornblende, and augite in a matrix of sandy clay. These materials fused into two distinct types of glass. The feldspars, clay material, and accessory minerals were the most fusible and molten glass derived from them must have been fairly mobile, for it shows marked flow lines best illustrated in Fig. 1, *A* and *B*.

The glass is colorless in thin section, and so the strong relief, shown by the dark flow lines in the left-hand part of Fig. 1, *A*, is due only to the differences in indices of refraction. The relief is accentuated by the inclined illumination used in photographing the glass.† The marked differences in the indices of refraction are confirmed by direct measurement.

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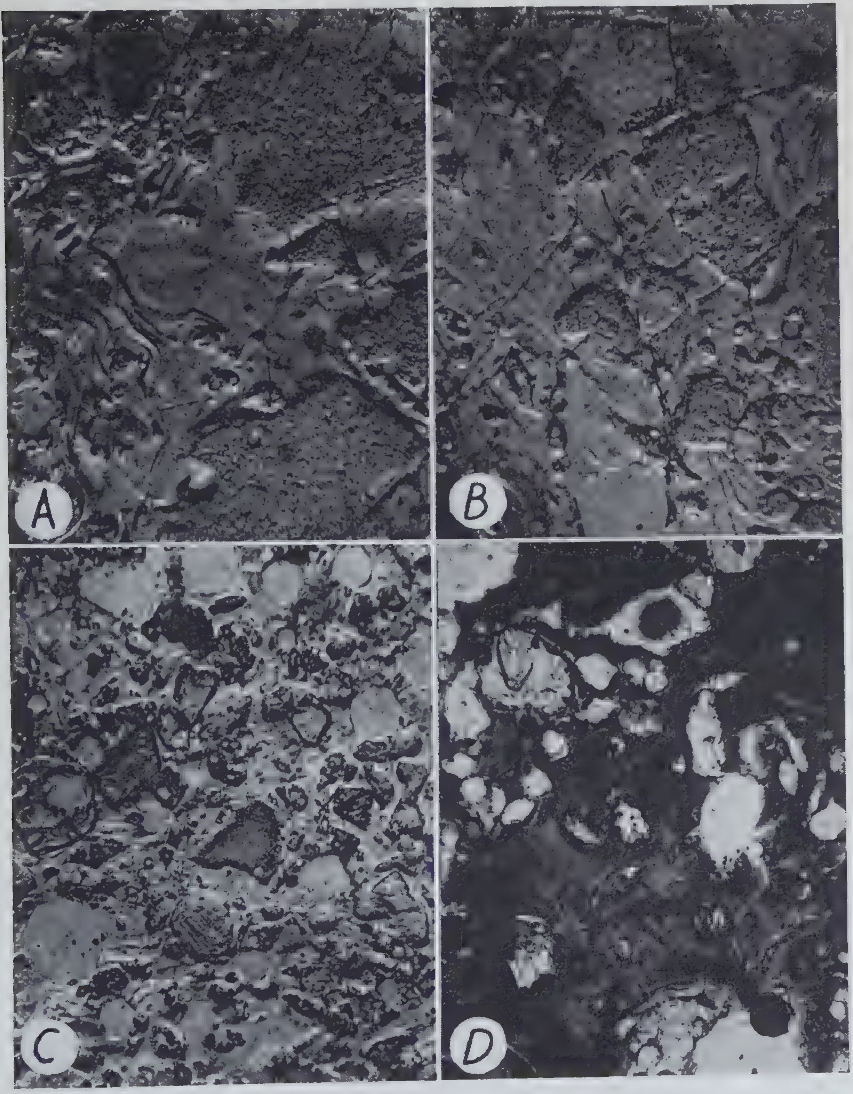

FIG. 1. Photomicrographs of glass from Alamogordo, New Mexico.

Most of the material ranges from $n=1.51$ to 1.53, but a little ranges as high as $n=1.54$, and a few areas, no doubt partly derived from ferromagnesian minerals, reach 1.55. Gas bubbles show in a number of places in Fig. 1, *B*, and a large one occurs at the bottom. The amount of flowage indicates that this glass was fairly fluid, for all movement must have occurred during the very short period during which so thin a layer could have remained molten.

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† Ross, Clarence S., Photomicrography by inclined illumination, *Am. Mineral.*, this issue, pp. 363–365.

Other areas in Fig. 1, *A* and *B*, present a very rough surface, and the low index of refraction, together with the inclined illumination, causes them to appear as depressions. The index of refraction is close to 1.46, indicating that this material is almost pure silica glass. The boundary between the glass derived from feldspar and clay, and that derived from quartz is very sharp, showing that there was little diffusion of one into the other during the brief time they remained molten. There is also evidence that the areas of silica glass underwent little or no distortion of shape due to movement. In other words, the silica glass must have been exceedingly viscous compared with the other glass. However, the silica glass commonly contains small gas bubbles as shown in the large area of silica glass in Fig. 1, *B*.

Silica glass forms normally by the fusion of cristobalite at 1713° C. However, when the temperature rises so rapidly that there is insufficient time for inversion to cristobalite, quartz can fuse directly to silica glass. The fusion point of quartz is not known accurately, but is thought to be slightly below 1470° C. The temperature of the explosion at Alamogordo, although unknown, must have been much higher than 1470° C. and reached so suddenly that the quartz present in the sand fused directly to silica glass.

The partly fused material is represented in Fig. 1, *C*. The low-index lighter-colored material in the groundmass is a porous glass, but scattered through it are residual masses of unfused, or only partly fused grains, which stand in relief. These are mostly quartz, but a striated grain just below the center of the photomicrograph is plagioclase. One small area was characterized by glass which is oxblood red in hand specimen. In thin section this material is highly mottled, as shown by the photomicrograph, Fig. 1, *D*. Varying shades of red are nearly black in photographic reproduction. Others, mottled gray in thin section, show as gray in the photomicrograph. The colorless areas are pigment-free silica glass. Spectrographic tests show that the material contains essential amounts of copper. By reflected light both the red and the gray areas give a metallic copper color. Thus it is evident that both the red and the gray colors are due to dispersed copper, the differences in color representing the degree of dispersion of the copper. The copper was probably derived from copper wire as copper minerals are not evident in the original arkosic sand.

PHOTOMICROGRAPHY BY INCLINED ILLUMINATION*

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Abstract

Differences in the indices of refraction may be the only physical property distinguishing different materials in some thin sections. This can be illustrated photographically by inclined illumination but the entire area photographed should be equally illuminated. Modifications of the illuminating system of a microscope by which this can be accomplished are described, and illustrated.

A method here described for making photomicrographs by means of strongly inclined illumination was found to be particularly useful for presenting the properties of the Alamogordo glass. The Alamogordo glass, except for a minor part containing copper, is completely colorless and isotropic in thin section, and so a difference in the index of refraction is the optical property which serves to differentiate the various materials and to emphasize the range in their optical properties.

The methods commonly used for measurement of indices of refraction by means of inclined illumination involve the introduction of a half shadow at some plane in the optical system of the microscope. This results in brilliant illumination of part of the microscope field, while the other part is in partial shadow. These lighting arrangements, which are entirely suitable for index-of-refraction determinations, and which have the advantage of quick change from parallel to inclined illumination, are not suitable for photographic presentation of differences in indices of refraction. For these reasons, a description of the illumination system used in the petrographic laboratories of the United States Geological Survey to overcome these difficulties will probably be of general interest.

A diagram (Fig. 1) illustrates the lighting system as applied to a petrographic microscope, but the same method could also be applied to a biological microscope. The essential feature is a reflecting surface (*D*) placed below the stage of the microscope. This may be constructed as an attachment which will clip over the upper condensing lens of the microscope or be inserted in place of that lens. A glass mirror may be used, but a stainless steel mirror is preferable. This mirror should be constructed so that the reflecting surface makes an angle of about 10 degrees with the horizontal when the carrier for the upper condensing lens, which supports it, is turned into full position. It is well to construct the attachment so that the reflection angle is slightly too great for optimum results when the carrier is in full position. Then the system can be adjusted for greatest contrast by turning the mount carrying the reflecting mirror slightly back from normal position, and adjusting the vertical position by means of the screw which controls the vertical position of the condensing system.

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A convenient light source is one which allows a rapid change from ordinary transmitted light to reflected light, and to inclined transmitted light. One light source serves all these uses, and is placed in a housing well back from the microscope, where it is out of the way of all manipulation. A small mirror (*C*) is permanently attached to the tube of the microscope about 10 centimeters above the front lens of the objective by means of a short extension rod. This has a hinge where attached to the microscope which allows it to be turned up against the tube when not in use, and another hinge above the mirror to permit the reflection of the beam into the proper position.

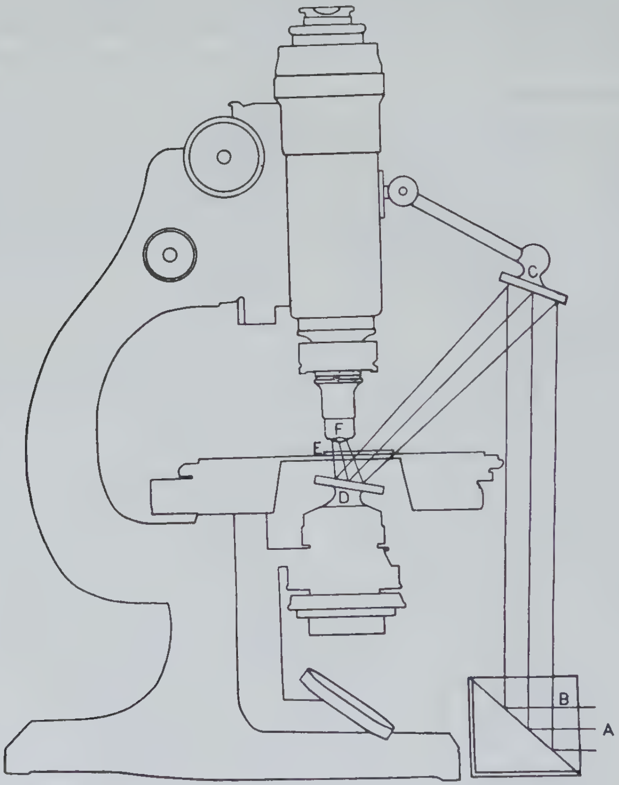

FIG. 1. Diagram of microscope equipped for microphotography by inclined illumination.

A light source which just covers the mirror of the microscope (about

5 centimeters in diameter) is desirable for the usual microscopic observations, but for reflected or inclined transmitted light a narrower and more concentrated beam is needed (about 1.5 centimeters in diameter). For this purpose a condensing lens of suitable focal length is used with the reflecting surface (*B*). A small concave mirror, such as that used by dentists, is attached at (*C*). The light beam in this system is reflected three times, and travels four paths before it enters the microscope, but this does not introduce undue optical complexities. The light leaves its source as a horizontal beam of parallel light, is reflected into a vertical beam, and due to the condensing lens travels as a slightly convergent beam to the mirror (*C*). Here it is reflected again and travels toward the microscope stage at an angle of about 45 degrees. It passes through the slide (*E*) and strikes the inclined mirror (*D*) where it is reflected again and enters the microscope objective (*F*) as an inclined beam, which strongly accentuates differences in indices of refraction. The vertical beam between (*B*) and (*C*) has the advantage that the microscope follows it during focusing.

The light is transmitted through the slide, and so this must have fair transparency; large colored or opaque areas tend to cast a shadow which would be noticeable in photographs.

The same equipment, but without the mirror (*D*), is useful for many other purposes including the examination of thin sections for identifying such materials as leucoxene, distinguishing pyrite from magnetite, or observing partial or complete alteration to hematite. If desirable, a film of polaroid may be placed above the reflector (*B*) giving almost complete polarization so that the equipment can be used in index of refraction measurements.

This method of inclined illumination gives best results with objective having a 16 or 25 millimeter focal length, but it is also good with the objective having a 40 millimeter focal length. Lenses with a very short working distance cut off the light from the inclined beam; the objective with a focal length of 9 millimeter is usable but does not give contrast equal to that produced by the others. This means that the usable magnifications range from about 25× to 80×, but at 150× the results are not so good.

The mirror (*C*) may be replaced by a direct light source. Either a vertical illuminating system such as that of Bausch and Lomb or the universal microscope lamp of the American Optical Company is suitable. The light should be fairly brilliant and a 20 to 25 candle-power lamp should be used.

GREEN LAZULITE FROM STODDARD, NEW HAMPSHIRE*

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Abstract

Lazulite found in Stoddard, New Hampshire, is unusual because of its dark-green color, high indicies of refraction, 1:1 iron-magnesium ratio, and polysynthetic twinning. *X*-ray photographs show the New Hampshire material to be identical in structure to blue lazulite from Kern County, California.

Introduction

A dark green variety of lazulite, at first believed to be apatite, is present in a small vein exposed on the southwest side of Jackson Hill in the northwest corner of the town of Stoddard, Cheshire County, New Hampshire.

A routine check on the mineral indicated that it was a variety different from those described in the *System of Mineralogy* (1) and by Meixner (3), so data on the New Hampshire material are presented here.

The vein is exposed for a distance of 70 feet, and varies in width from 6 to 18 inches. It strikes N 60° E and dips 45° to the northwest, and is enclosed in a mica schist in which the vertical foliation strikes N 42° E. The vein consisted largely of quartz and muscovite with irregular masses of lazulite up to three inches in diameter and a few tabular crystals of columbite-tantalite.

Chemical Analysis

The first clue to the identity of the green lazulite was obtained from an analysis of the mineral given in Table 1. The analysis is similar to published analyses, but the ratio of iron to magnesium is unusually large (1:1 molecularly).

Table 1. Chemical Composition of High Iron Lazulite

	1	2	3
MgO	6.45	.160	1
FeO	11.58	.161	1
Al_2O_3	31.83	.318	2
H_2O	5.19	.288	1.8
P_2O_5	45.10	.318	2
	100.15		

1. Analysis by F. A. Gonyer.
2. Weight percentages divided by molecular weight.
3. Oxide ratios.

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* Contribution from the Department of Mineralogy and Petrography, Harvard University, No. 297.

X-RAY DATA

A comparison of the *x*-ray powder photographs of the dark green New Hampshire material with blue lazulite from Kern County, California, shows that the two are identical in structure. However, the data in Table 2 differ considerably from that given by Kerr (2) for material from White Mountain, California.

TABLE 2. INTERPLANAR DISTANCES AND ESTIMATED INTENSITIES OF NEW HAMPSHIRE AND CALIFORNIA LAZULITE

Lazulite, Stoddard, N. H. Cu Radiation, Nickel Filter		Lazulite, White Mountain, California	
d	*I*	*d*	*I*
4.64	1	6.13	2
3.20	10	4.79	2
3.16	4	3.15	10
3.10	4	2.59	4
3.035	4	2.265	4
2.525	5	2.000	5
2.335	1	1.825	4
2.242	3	1.770	1
2.200	3	1.705	2
2.040	1	1.640	4
1.987	4	1.568	5
1.965	4	1.420	3
1.794	1	1.340	1
1.778	1	1.285	4
1.604	3	1.255	0.5
1.588	3	1.190	2
1.554	8	1.120	1
1.526	4	1.085	0.5
1.430	1	1.035	0.5
1.402	2	.997	1
1.380	1		
1.265	6		
1.177	1		
1.106	1		
1.087	1		

PHYSICAL PROPERTIES

A number of physical properties of the New Hampshire material differ from those obtained from lazulite elsewhere. Some of its optical properties are different, presumably because of the unusually high percentage of iron. A summary of the optical properties is as follows:

$n_{Na} \pm 0.001$	
$\alpha = 1.634$	Opt. (−)
$\beta = 1.659$	$2V = 63°$
$\gamma = 1.668$	$r < v$, moderate

Pleochroism
X = Yellow
Y = Yellowish green
Z = Bluish green

Thin sections of the material showed well-defined polysynthetic twinning. Parting has developed along the twin planes.

ACKNOWLEDGMENT

The identification and determination of some of the characteristics of the high iron lazulite were made possible by Professor Esper S. Larsen of Harvard University who provided the analysis, laboratory facilities, and friendly counsel.

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NOTES AND NEWS

THERMAL METAMORPHISM OF TILLITE AT ALTA, UTAH

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The occurrence of tillite in Utah is well known from the findings of Blackwelder, Hintze, Eardley and others,[1] and many localities have been noted and the tillite described. In the Cottonwood-American Fork region 14 miles southeast of Salt Lake City, near the old ghost mining town of Alta, the tillite has been thermally metamorphosed by the Cottonwood granodiorite with the development of several interesting features.

General Geology

Calkins'[2] map of the Cottonwood-American Fork region includes the area where the specimens for this study were collected. Here, at the bottom of Little Cottonwood Canyon, the sedimentary rocks strike nearly north-south and dip steeply toward the east. The tillite is nearly a thousand feet thick and is interbedded in quartzite. The age of the tillite has been determined as late Proterozoic by workers who have studied the formation. To the west, the contact of the Cottonwood granodiorite, which trends generally north-south, is to be found several hundred feet below the bottom of the tillite next to quartzite. The Cottonwood granodiorite is a stock which outcrops in an area of about 25 square miles. The tillite can be traced several miles northward to Big

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Cottonwood Canyon, where, according to R. E. Marsell of the University of Utah, it reaches a total thickness of 3000 feet. The rock there seems to be little changed by thermal effects and samples of this unaltered tillite were studied for comparison with the metamorphosed material.

NORMAL TILLITE

Unchanged tillite is generally a hard, dense, blackish to gray, gritty "argillite" which contains scattered pebbles and boulders. The pebbles range in size from ¼ inch to boulders several feet in diameter and all are usually rounded to subangular. Rock types represented are quartzite, gneissoid granite, vein quartz, cherty dolomite and marble with the percentages of each varying widely in different areas.

Under the microscope the matrix appears to be composed principally of rounded to very angular fragments (.5–1 mm. diameter) of quartz with subordinate amounts of orthoclase, microcline, and plagioclase. Small lithic fragments of carbonaceous shale, quartzite, limestone or marble, and granite are also found. In between the grains is a dark carbonaceous flour-like material too fine for microscopic identification. A little sericite and chlorite has developed in the matrix evidently due to incipient load metamorphism.

METAMORPHOSED TILLITE

The fresh broken surface of metamorphosed tillite matrix shows a vitreous lustre and a brownish amber color. The rock is extremely hard where the texture is fine and uniform. Pebbles of quartzite and granite appear to be entirely unchanged. No limestone or marble fragments are at all in evidence and their place is apparently taken by greenish patches of a bladed mineral. The patches vary in size from ¼ inch to several inches in diameter and present an extreme variety of outline as well as internal structure. Surrounding each green mass is a light colored band varying in thickness up to 5 mm. which grades outward from a light green to nearly white, and then grades into the amber colored matrix. This gives them a zoned appearance which is best observed on a fresh surface but is also quite noticeable on a weathered surface. The central part is often weathered out deeply while the outside zone stands up in a rim. The green blades always develop with random orientation and sometimes show voids between the blades which occasionally are filled with pyrite. The microscope reveals that the dense indeterminate matrix of unmetamorphosed tillite has been recrystallized principally to biotite with interstitial quartz and a black opaque dusty substance which is probably graphite. The dimensions of the biotite flakes are usually in the range of

.05 mm. to .2 mm., though larger flakes are seen in occasional patches.

The fragments of the matrix have undergone little change. Quartz, orthoclase and plagioclase are very clear in appearance and their outline seems to be approximately the same as in the unaltered rock. The green bladed mineral was identified as actinolite with pleochroism in various shades of green and optical properties as follows: $c \wedge Z$ 18°, $\alpha=1.617$, $\beta=1.632$, $\gamma=1.641$; $\gamma-\alpha=.024$, $2V=78°$ and optically (−). The color varies in different specimens from pale green to nearly colorless indicating that the iron content is not constant throughout. The green masses as a whole are composed entirely of actinolite, the larger of which show a central fine textured aggregate surrounded by a rim of coarse crystals with a sharp boundry between. (Fig. 1).

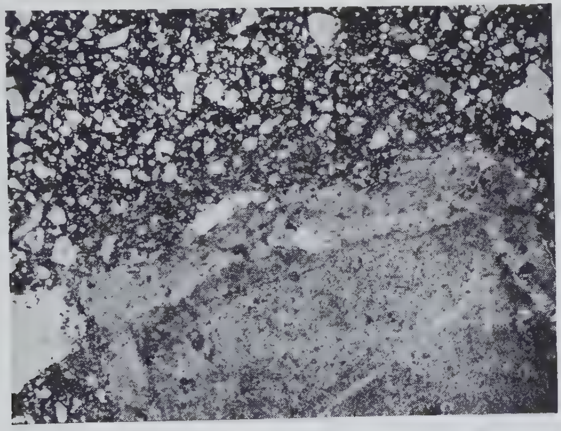

Fig. 1. Photomicrograph of tillite. × 5. Large nearly square actinolite mass in matrix shows small crystals in core (lower right center), border zone of coarse crystals and the outside replacement zone. The matrix is composed of quartz fragments (light) and fine grained biotite with dusty graphite (dark).

Usually outside of the solid actinolite there is a zone up to a maximum width of 5 mm. where actinolite needles replace the matrix and fragments alike (Fig. 1). In this zone also are found a few idioblastic crystals of sphene. Small crystals of actinolite are sometimes found in the matrix mixed with biotite, but these areas are somewhat restricted and can be seen only in thin section.

Metamorphism

The metamorphic features described above are found only in the tillite which is near the Cottonwood stock and consequently are presumed to be the result of the rise of temperature consequent to the intrusion.

There are no evidences of introduction of material into the rock, hence all of the new mineral development must be accounted for by reconstitution of the original rock materials.

The biotite, actinolite, and graphite of the groundmass are considered normal developments from a glacial rock flour consisting of fine particles of quartz and limestone or dolomite, clay, carbonaceous and ferruginous materials. It is believed that the solid actinolite masses have developed from the formerly existing limestone and dolomite fragments. An interesting problem connected with diffusion in metamorphism is presented by most of these masses. As previously stated the rim usually has developed large crystals while the center may contain finer grained actinolite, and outside the coarse rim actinolite replaces the matrix in decreasing amount for a distance of about 5 mm. It would be expected that when a rise of temperature takes place the most vigorous development of new crystals would be at or near the boundary of the two substances involved, hence the coarse actinolite on the rims. Slower diffusion would allow silica and iron to penetrate farther into the carbonate masses but smaller crystals would result. Calcium and magnesium oxides have escaped beyond the coarse rim causing the development of the replacing actinolite. According to Harker,[3] diffusion in metamorphism is restricted to a distance of "a small fraction of an inch." Evidences here would confirm this supposition. The presence of sphene in the outer replacement zone only can be explained by the presence here of calcium and titaniferous materials in the original deposit.

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DIFFERENTIAL THERMAL CURVE OF SIDERITE

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While working on the mineralogy of a drill core of bauxite (1) it was found necessary to determine the standard differential thermal curve of siderite. A search of the literature for data on this mineral revealed that only Speil (2) had described the curve. He listed a strong endothermic peak at 590° C. and an exothermic reaction at about 720° C. The siderite curve published by Berkelhamer (3) shows a very strong endothermic reaction. After this reaction the curves goes a considerable distance above the base line but he evidently does not consider this as an exothermic reaction because he makes no mention of it.

Just before the bauxite investigation was completed Cuthbert and Rowland (4) published a new curve for siderite. Using siderite from the same locality, Roxbury, Connecticut, the writer was unable to duplicate their results.

Recently Kerr and Kulp (5) have published differential thermal curves for siderite from various localities. The curves all show both endothermic and exothermic peaks.

Both an endothermic and an exothermic peak should be expected for this mineral. Kelley and Anderson (6) list the following data for siderite:

$FeCO_3$	$FeO + CO_2$	$\Delta H = 19{,}790$ cal/mol
$3FeO + O$	Fe_3O_4	$\Delta H = -73{,}000$ cal/mol
$2FeO + O$	Fe_2O_3	$\Delta H = -66{,}000$ cal/mol

They found that the dissociation of siderite to ferrous oxide and carbon dioxide is an endothermic reaction with a heat of dissociation of 19,790 calories per mol. From similar thermodynamic calculations they found that the oxidation of the resulting ferrous oxide to either Fe_3O_4 or Fe_2O_3 is a strong exothermic reaction. They calculated that the dissociation temperature comes at 459° C., but state that this temperature seems too low. The differential thermal curves show, however, that siderite starts to dissociate at almost exactly this temperature.

The ferrous oxide undoubtedly oxidizes to Fe_3O_4 because all of the samples, after dissociation, were strongly ferromagnetic. Whether or not Fe_2O_3 also forms has not as yet been determined.

Kerr and Kulp mention that "The cause of the reported exothermic peak is not clear." The above explanation should clear up this point. They also raise the question as to whether or not the oxidation of the ferrous oxide to the ferric state is fast or slow. The curves obtained show that the rate of oxidation is very fast and that the reaction takes place immediately after the removal of the CO_2.

On the basis of the above data and a curve in the unpublished thesis of Beck (7) (that is essentially the same as those listed by Kerr and Kulp), it seems clear that the exothermic peak as well as the endothermic peak has been established for siderite.

The reason for the different results obtained by various authors using the same material is not clear. The writer has found, however, that some of the discrepancies are due to differences in sensitivity of the equipment used. Our curves were obtained by the use of a differential thermal apparatus using a recording ammeter and an amplifyer constructed by Mike Frueh under the direction of Dr. H. W. Fairbairn in the geology laboratory of the Massachusetts Institute of Technology.

Samples of a drill core of bauxite were tested in this instrument and in one in the ceramic department of M.I.T. that is the same as the apparatus described by Berkelhamer (3) which utilizes a photographic method of recording. The resulting curves, which will be published soon, are quite different for the two types of recording apparatus. The electronic method of recording seems much more sensitive than the photographic method.

On the basis of the above observation it would seem advantageous for workers in this field to exchange samples in order to evaluate the influence of different instrumental characteristics on the thermal curves for the common clays and carbonates.

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MODE OF OCCURRENCE OF TITANIUM AND ZIRCONIUM IN LATERITES

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Titanium

Although titanium is commonly present in amounts up to three or four per cent in some bauxites and laterites, frequently no titanium mineral can be visibly identified. During an investigation (5) of a drill core of Arkansas bauxite it was found that the titanium occurs in at least four different forms:

(1) As sphene.
(2) As ilmenite.
(3) As one of the polymorphous forms of TiO_2, principally brookite.
(4) In substitutional solid solution in the aluminum minerals.

Sphene was observed in thin sections and was collected from several horizons in the drill core. The products from concentration experiments reveal that sphene dissolves readily when exposed to circulating solutions. When the sphene occurred enclosed in pisolites it was preserved from the attacking solutions and is less corroded than that collected from portions of the core that contained no pisolites.

A black mineral is found throughout the core. In places the grains are quite large but the usual appearance resembles "pepper" disseminated through a given specimen. *X*-ray photographs of this black mineral indicate that it is ilmenite. It alters to a yellow, earthy-appearing substance commonly occurring as pseudomorphs after ilmenite.

Several concentrates of the yellow mineral were made and checked by *x*-ray methods. One concentrate was prepared by rolling the altered ilmenite grains between two thin section glasses. Ilmenite rolls off the glass leaving the yellow mineral behind, if the slide is first rubbed with a finger to insure a very slight film of oil on the glass. This concentrate yielded an *x*-ray pattern identical with brookite.

Another concentrate of yellow grains yielded patterns indicating the presence of brookite, ilmenite, and the probable presence of a small amount of anatase. Also a small amount of sphene was present in one of the concentrates.

A spectrographic analysis of a carefully cleaned sample of the yellow material revealed the presence of the following elements:

ELEMENT	ESTIMATED PERCENTAGE
Ti	Large
Fe	0.5–1.0
Zr	small (0.3)
Al	1.0–1.5
Ca	1.0–1.5
Si	Trace

The iron and the zirconium undoubtedly replace titanium in solid solution; the calcium indicates that a small amount of sphene is present as an impurity along with the aluminum.

This yellow material is evidently what many authors describe as xanthitane. Some of the other names applied to this yellow mineral, and their relationship to other forms of TiO_2, are of interest. According to Dana (4):

1. "Leucoxene, xanthotitane, xanthitane, and hydrotitanite are all identical with anatase.
2. Anatase is polymorphous with brookite and rutile.
3. Leucoxene is a name loosely applied to dull, fine grained, yellowish to brown alteration products high in titanium. It is found as an alteration product of sphene, ilmenite, perovskite, titanium magnetite, or other titanium minerals. The material consists in most instances of rutile: also, less commonly, of anatase, or sphene."

The leucoxene of Coil (3), the xanthitane of Coghill (2), and others, is, then, one of the polymorphous forms of TiO_2. In this case, it is brookite.

The hydrates of titanium oxide, $TiO_2 \cdot H_2O$ and $TiO_2 \cdot 2H_2O$, have been described (6), but very little is known about their solubility. The unhydrated oxide does not dissolve appreciably in either acids or bases: the hydrated forms are somewhat soluble in both.

The alteration of ilmenite or sphene to brookite must obviously be a reconstructive transformation.* Because the transformation took place in an aqueous medium, the individual atoms, or atom groups involved in the transformation, must have been hydrated at one time or another. Large, recrystallized particles (they are recrystallized because they yield an *x*-ray diagram) have only adsorbed water; smaller particles or atom groups (in the colloidal range of sizes) may behave as gels, whereas still smaller units form true hydroxides:

$$TiO(OH)_2 \rightarrow TiO^{++} + 2OH^- \qquad \text{[See Latimer (6)].}$$

If enough solution is present, the process of hydration can go to completion, that is, it may convert all of the unhydrated material into titanate ions; if only a limited amount of solution is present, it might act as a transporting medium through which the ions involved in the reconstructive transformation could travel. These ions could then order themselves and develop into one of the polymorphs of TiO_2. When enough data are gathered on this subject, it may be possible to reconstruct the type of environment in which a particular polymorph of TiO_2 was formed in preference to some other form.

If titanium can travel in solution as a gel or as titanate ions, it is not necessary to resort to explanations such as compaction (1) to account for concentrations of titanium in clay and bauxite deposits.

ZIRCONIUM

It is interesting to note that the only places in the core where zirconium is found in the form of zircon crystals is in the pisolites. Well formed zircon crystals are found in red, unleached pisolites containing gibbsitized feldspar remnants. In the pisolites that have been leached by later solutions the remaining zircons show corroded, irregular outlines indicating that they are gradually going into solution.

The chemistry of zirconium is quite similar to that of titanium. The only oxidation state of zirconium stable in water solutions is +4. The dioxide of zirconium is somewhat more basic than titanium dioxide and, when hydrated, dissolves fairly readily to form the zirconyl ion, ZrO^{++}:

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* A reconstructive transformation is one in which a crystal structure is destroyed and some or all of the resulting atoms recombine to form a different structure. It contrasts with displacive transformations which involve only a slight displacement of parts of the structure. If a certain critical temperature is passed, displacive transformations of the high-low type instantaneously occur (example: low-quartz to high-quartz).

$$ZrO(OH)_2 \rightarrow ZrO^{++} + 2OH^-.$$

The solubility of the oxide in alkaline solution is slight and the zirconates are much less stable than the titanates (see Latimer (6)).

Zirconium, then, is removed in solution more easily than titanium and does not form secondary zirconium minerals. The large percentage of the zirconium determined in the spectrographic examination must be as zirconate ions adsorbed on the aluminum hydroxide minerals.

Because the ionic potentials† of titanium (2.43^{+4}), zirconium (2.24^{+4}) and aluminum (2.45^{+3}) are almost equal, the first two substitute for Al in the various aluminum minerals.

Zirconium was also found in a concentrate of yellow brookite, indicating that Zr^{+4} also substitutes for Ti^{+4} in some of the titanium minerals.

Because titanium, zirconium, and uranium form similar ions under certain conditions they should be closely associated:

$$\begin{array}{ll} TiO(OH)_2 & TiO^{++} + 2OH^- \\ ZrO(OH)_2 & ZrO^{++} + 2OH^- \\ UO_2(OH)_2 & UO_2^{++} + 2OH^-. \end{array}$$

This subject will be discussed in a separate paper now in preparation.

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3. COIL, F., Chemical composition of leucoxene in the Permian of Oklahoma: *Am. Mineral.*, **18,** 62–65 (1933).
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5. FREDERICKSON, A. F., The mineralogy of a drill core of Arkansas bauxite: *Sc.D. Thesis*, Massachusetts Institute of Technology (1947).
6. LATIMER, W. M., The oxidation states of elements and their potentials in aqueous solutions: Prentice-Hall, Inc., New York (1938).

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† Ionic potential $= Z/r$ where $Z =$ valence of the ion and $r =$ the ionic radius.

THE NATIONAL RESEARCH COUNCIL HAS APPOINTED A COMMITTEE ON GEOPHYSICS, ADVISORY TO THE OFFICE OF NAVAL RESEARCH

Acting upon a request from Admiral Paul F. Lee, Chief of Naval Research, the National Research Council has appointed a Committee of active scientific investigators to advise the Geophysics Branch of the Office of Naval Research regarding scientific and related aspects of their research programs. The Committee is as follows:

> Walter H. Newhouse (Chairman), Harry H. Hess (Vice Chairman), Roland F. Beers, Maurice Ewing, Ellis A. Johnson, Lester E. Klimm, William C. Krumbein, William W. Rubey, and J. Frank Schairer.

Dr. R. C. Gibbs, Chairman of the Division of Mathematical and Physical Sciences of the NRC, acts as Administrative Adviser to the Committee, in collaboration with Dr. Arthur Bevan, Chairman of the Division of Geology and Geography.

The Committee held its first meeting on January 7 and 8, 1948, in Washington, D. C. As stated by Dr. Roger Revelle, Head of the Geophysics Branch of the Office of Naval Research, that Branch is charged with the responsibility within the Navy Department of sponsoring basic research in appropriate fields of earth sciences through financial and other support of worthy projects. Functioning within this general framework of responsibility the Committee will, for the present, restrict its consideration to research problems dealing with the crust of the earth and the properties of the earth as a whole.

Since it is part of the policy of ONR to sponsor research in fields not adequately covered by other agencies, the Geophysics Branch, with the Committee's concurrence, has established the following objectives for Research within the fields covered by the Committee:

1. To foster, in cooperation with other agencies, geological, geographical, and geophysical explorations of little known area of the earth such as the islands of the Western Pacific and the Arctic and Antarctic. Such exploration may include all aspects of the natural environment and problems of human and economic geography and ethnography as well as the more limited objectives implied in the terms geology and geophysics.
2. To conduct laboratory and field studies leading to a greater understanding of the properties and processes existing in the outer hundred kilometers of the earth's crust.
3. To develop instruments and techniques for determination of the earth's properties; for example, universal airborne magnetometer equipment.

The Office of Naval Research has adopted the policy of avoiding formulation, detailed direction, and "farming out" of projects for basic research in the belief that maximum progress and results will be realized if projects for investigation grow out of the ideas and interests of the investigators themselves. The Committee warmly endorses this policy and will seek at all times, through advice and recommendations, to further its operation to the maximum degree possible. The submission of significant and well-organized research proposals will be helpful in this connection.

The Geophysics Branch of ONR has asked the Committee

1. To advise it on the over-all objectives of the ONR basic research program in this field.
2. To encourage the submission of worthwhile research proposals.
3. To evaluate the scientific merits of proposals received and recommend appropriate action thereon.

The Advisory Committee on Geophysics has formulated, chiefly for its own guidance certain bases for evaluating research proposals, as follows: (These are subject to change as further experience may indicate. The order of listing at any point is not to be regarded necessarily as the order of importance.)

1. General.
    a. Preference should be given to specific individual proposals in contrast to multiple proposals, the several parts of which are not closely related.
    b. It is desirable that proposals be submitted in the name of the individual or individuals who will be actively engaged in the proposed investigations.
2. Scientific Merits.
    a. Would the solution of the problem be important to the progress of the science of Geophysics; that is, would the solution lead to new problems rather than to a cul de sac?
    b. Does the problem appear capable of solution by the techniques proposed?
    c. Will the conduct of the research lead to valuable training of younger scientists?
    d. Does the problem to be investigated lie within the Research objectives of the Geophysics Branch of ONR?
    e. Are important unforeseen results likely to come out of the research?
    f. Is the investigation timely in relation to other contributary operations?
3. Qualifications of the investigator and adequacy of proposed project.
    a. Are the training, experience, and demonstrated ability of the principal investigator suitable for the project?
    b. Are the assisting personnel and the equipment available for the project adequate?
    c. Is the budget submitted commensurate with the requirements of the project?
4. Possibilities of undesirable duplication.

For further details consult the Office of Naval Research, Navy Department, Washington 25, D. C., or the National Research Council, 2101 Constitution Avenue, Washington 25, D. C.

International Geological Congress
XVIII Session—Great Britain, 1948
General Secretary: Geological Survey and Museum,
Exhibition Road, London, S.W. 7

29th January, 1948

Dear Dr. Aldrich,

Thank you very much for your letter of January 7th. Professor Read certainly found his visit and the welcome you gave him most enjoyable and stimulating.

He tells me that he found that certain difficulties in obtaining shipping passages are being experienced by American geologists who wish to join the Congress, and I have received directly one or two complaints and enquiries about the same point. I have taken the matter up with Cooks and with Cunard White Star (who gave us assurances some time ago that traffic to the Congress could be adequately handled); and they are doing all they can from this end to make sure that members are accommodated and that their American offices are alive to the urgency of the situation. Cooks think that the trouble may be in part that it is not always possible at the moment to assure an applicant of a specific sailing date, even though there is no doubt that it will eventually be possible to provide a berth for him about the time he specifies. I understand that additional boats are very likely to be brought into service on the Atlantic route before the summer: but that negotiations on this are not yet quite complete.

Professor Read also found that some American colleagues were dubious about coming over here and making further inroads upon our food supplies. There may also be the very understandable point as to whether it is worth making the trip in view of reports of meagre fare here.

It seems likely that the food situation probably appears worse, in Press reports, than it actually is. We cannot in present circumstances entertain Congress members as lavishly as we should wish. Nevertheless, we have done our best to provide for the comfort and refreshment of members, and think that they may find conditions less rigorous than reports abroad may suggest.

I may mention that, in addition to Government, University and other receptions in London, a large number of civic authorities, industrial firms and other bodies are arranging special local hospitality for the excursion parties.

We greatly hope that despite any present discouraging factors, the number of members from U.S.A. and Canada will approach the number (some 500, including relatives) who provisionally registered in response to the Third Circular. It was largely because of this great response by prospective members from North America that we further extended last autumn our excusion programme; and the success of the Congress will largely depend upon their presence.

Please be assured that on our part we shall spare no effort to satisfy the needs of our guests.

Yours very sincerely,
A. J. Butler,
General Secretary

Dr. H. R. Aldrich,
The Geological Society of America,
419 West 117th Street,
New York 27, New York, U.S.A.

The editor of the Industrial Diamond Review has a limited number of reprints available for free distribution on recent scientific and technical progress in the diamond industry. The reprints include articles on General (diamond industry), Physical Properties, X-ray Crystallography and Radiography, Surface Finish, Diamond Polishing, Shaped Diamond Tools, Truing of Grinding Wheels, Diamond Dust and Diamond Grinding Wheels, Diamond Dies, Cutting and Machining of Glass, Diamond Drilling, Sapphire and Jewel Bearings, Hardness Testing, and Historical Aspects. Anyone interested in securing reprints should address: Industrial Diamond Review, 226 Latymer Court, Hammersmith, London, W.6.

Dr. Robert A. Dryer, associate professor of geology, has been appointed chairman of the department of geology at the University of Kansas. He succeeds Professor L. R. Laudon who has accepted a position at the University of Wisconsin.

CORRECTION

In the paper entitled "Relations Among Crystallographic Elements" by H. T. Evans, Jr. (*Am. Mineral.*, **33**, 60–63 (1948)), three typographical errors occurred in Table 1, as follows:

Formula (4) should read $$v_2 = \frac{\sin \nu}{\sqrt{1 + (x_0' \cos \nu - y_0' \sin \nu)^2}}$$

Formula (7) should read $\cot \alpha = x_0' \cos \nu - y_0' \sin \nu$

Formula (10) should read $x_0' = \cot \beta$

Formula (7) in the original paper was followed by a superscript, which is a reference to a footnote, and not to be confused with a square term.

Howard T. Evans, Jr.

NRC NEWS ITEM

The National Research Council has recently appointed a group of leading chemists, physicists and mineralogists, whose interests make them specially qualified, to act as Provisional Executive Committee of the American Section of the International Union of Crystallography. This Union which was formed in 1947 has undertaken the publication of an international journal of crystallography, *Acta Crystallographica*, and is planning for the continuation of the *Strukturbericht* and for the publication of a new edition of the International Crystal Structure Tables. The new Union plans to hold its first General Assembly and Congress at Harvard University from July 28th to Aug. 3rd 1948. The membership of the American Committee consists of Professor L. O. Brockway, University of Michigan; Professor M. J. Buerger, Massachusetts Institute of Technology; Professor J. D. H. Donnay, The Johns Hopkins University; Professor I. Fankuchen, Polytechnic Institute of Brooklyn; Professor C. Frondel, Harvard University; Dr. D. Harker, General Electric Company; Dr. M. L. Huggins, Eastman Kodak Company; Professor A. L. Patterson (Chairman), Bryn Mawr College; Professor L. Pauling, California Institute of Technology; Professor F. Seitz, Carnegie Institute of Technology; Professor A. N. Winchell, American Cyanamid Company and Dr. R. W. G. Wyckoff, National Institute of Health. This committee will act as advisory body to the National Research Council on the relationships between the crystallographers of the United States and the new Union. In addition to these duties the committee will recommend to the National Research Council a permanent constitution for the American Section of the Union and will also advise the Council with regard to any matters which are of general concern to crystallographers in the United States.

NOMINATING COMMITTEE OF THE MINERALOGICAL SOCIETY OF AMERICA

The officers and fellows of the Mineralogical Society of America are nominated by the Council at its annual meeting. The Council is guided in its choice by recommendations made by the Nominating Committee.

It is the feeling of the Council that the general membership and fellowship should have more voice in suggesting nominees. Therefore, the Council has voted that the names of the members of the Nominating Committee be published so that those wishing to make recommendations for officers and fellows can communicate with one of the members.

The present Nominating Committee appointed by the President, Martin A. Peacock, is as follows:

H. H. Hess, *Chairman*, Department of Geology, Princeton University, Princeton, N. J.

H. W. Fairbairn, Department of Geology, Massachusetts Institute of Technology, Cambridge 39, Massachusetts.

J. E. Hawley, Department of Mineralogy, Queen's University, Kingston, Ontario.

L. C. Ramsdell, Mineralogical Laboratory, University of Michigan, Ann Arbor, Michigan.

George Tunell, Department of Geology, University of California, Los Angeles 24, California.

C. S. Hurlbut, Jr., *Secretary*

A very unfortunate omission appears in the list of Correspondents recently published in the March-April issue of the Journal. The list should include the name of Professor C. E. Tilley of the University of Cambridge, England.

BOOK REVIEWS

LES MINÉRAUX DE BELGIQUE ET DU CONGO BELGE. H. BUTTGENBACH, Professeur émérite de l'Université de Liége, Membre de la Classe des Sciences de l'Académie Royale de Belgique et de l'Institut Royal Colonial Belge, Correspondant de l'Académie des Sciences coloniales de Paris. Paris, Dunod, éditeur, 92, rue Bonaparte (VI^e). Liége, H. Vaillant-Carmanne, S. A., imprimeur, 4, place St.-Michel **(1947)**. Printed in Belgium. xviii+574 pages, 16 by 24 cm., 17 plates, 1 folding map, 397 figs. Bound in half cloth. Price, 800 Belgian francs.

Data, most of them published and some unpublished, on the 309 mineral species known to occur in Belgium (76 species), in the Belgian Congo (134 species), or in both (99 species) have been gathered in this critical compilation; 16 minerals were first found in Belgium, 39 in the Belgian Congo. Only those characters are mentioned that were observed on material from these two countries; for rare species, however, a more complete characterization is given. Each species is described according to the following plan: name, chemical formula, crystal system or crystal class, accepted axial elements with their source, list of forms (observed on Belgian and Congolese crystals) symbolized in both Lévy and Miller notations, complete discussion under the headings "Belgium" and "Congo." As in his textbook[1] the author uses a different notation for rhombohedral and hexagonal crystals and he still treats the five trigonal classes as rhombohedral, regardless of lattice mode. The bibliography of each species is conveniently placed after its description. The 397 hand-lettered crystal drawings are uniformly very good, the forms being designated by the compact and descriptive Lévy symbols. Excellent photographs, for most of which the scale is unfortunately missing, are presented in 17 plates on glossy paper. The author has made a special effort to ascertain the geological occurrences of each mineral—a none-too-easy task, in which he occasionally concedes defeat!

This volume should prove quite serviceable as a reference book for it is very carefully indexed. In addition to the systematic tabulation of the species in the introduction, and their alphabetical listing at the end of the book, a geographical index gives the localities (separately for Belgium and the Belgian Congo) and, under each locality, the minerals found there. The Congolese index refers to a large and easily legible sketch map (scale: 1/5,000,000). The paper is good and the printing, with few typographical errors for a work of this sort, is up to Vaillant-Carmanne's usual excellence.

Professor Buttgenbach retired in 1945, after having taught at Liége for nearly a quarter of a century. The cruel blow he suffered in the 1944 destruction of his beautiful museum evidently did not subdue his energy, and his friends will rejoice at his continued activity. *Ad multos annos!*

J. D. H. DONNAY, *The Johns Hopkins University*

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[1] Review in *Am. Mineral.*, **21**, 211–212 (1936).

GEMS AND GEM MATERIALS, by EDWARD H. KRAUS AND CHESTER B. SLAWSON. McGraw-Hill Book Company, Inc. Fifth Edition, **1947**. 332 pages and 403 illustrations.

The revised fifth edition of this text will be very welcome to amateurs and students of gem materials alike. Compared with the third edition (see this Journal, vol .24, p. 461, 1939) it has been somewhat expanded by addition of tables of absolute hardness, dispersion, and statistics of diamond production. The discussion of specific gravity has been made complete by illustrating and describing Krätschmar's balance. Other additions are paragraphs on distorted crystals, the property of parting, piezo-electricity, illustrations of the "diamondscope" and "diamolite" and irradiation of gems. The dichroscope is explained more fully by the addition of a line drawing. The polariscope (a new model designed by Shipley) is described for the first time in the fifth edition. The chapters on cutting of gems including differential hardness in diamonds, and on synthetics are well balanced and up to date.

The chapter on Crystal Structure and X-ray Methods is well illustrated, but it is doubtful that anyone without further instruction could understand such a short treatment of a difficult subject. The 14 Bravais space lattices as illustrated should puzzle him especially.

This, as the earlier additions, contains among a multitude of good photographs a number which do not *show* the features which they are supposed to *convey*. It is very doubtful that any picture but a colored one could convey the appearance of a ruby in a piece of limestone or cassiterite with fluorite, to mention only two of the examples. The four colored plates of the third edition have been left out. The bibliography is well selected. The tables of physical properties are complete and should be very useful but are unfortunately printed in too small a type to appeal to the reviewers.

The publishers have used such a thin though good grade of paper that the book appears to be much less voluminous than previous editions in spite of its 332 pages. It has been possible by this means to hold the price to $4.00.

J. W. Gruner and Lynn Gardiner, *University of Minnesota*

NEW MINERAL NAMES

Billietite

J. F. Vaes, Six nouveaux mineraux d'urane provenant de Shinkolobwe (Katanga). *Bull. Soc. Belge Geol.*, **70,** B 212–225 (1947).

R. Van Tassel. Analyse spectrale de la billietite. *Ibid.*, p. 226 (1947).

This mineral occurs as small (up to 2 mm.) tabular, amber-yellow crystals, resembling becquerelite. Orthorhombic, pseudo-hexagonal; most crystals are twinned on (111), one crystal was twinned on (101). Forms observed: (110), (011), (101), (111). Cleavage, (010) perfect. Optically negative, $nX=b$, about the same as n of old methylene iodide (1.74?), $nY=c$, a little less than that of becquerelite, $nZ=a$, a little less than that of becquerelite, $2V=36°$. Pleochroism strong, nX nearly colorless, nY greenish yellow, nZ amber brown, dispersion strong $r>v$. Qualitative chemical tests showed the presence of Ba, U, and H_2O; this was confirmed by spectrographic tests which also showed a little lead to be present. Easily loses water when heated. Named for Valère Louis Billiet, 1903–1945, Belgian mineralogist.

Michael Fleischer

Vandendriesscheite

J. F. Vaes, *op. cit.*

Small, amber-orange, pseudo-hexagonal barrel-shaped crystals, up to $1\frac{1}{2}$ mm. Orthorhombic, forms: (010), (110), (111), (100); cleavage (010) perfect. Optically biaxial, negative, $nX=b$, not measured, $nY=a$, and $nZ=c$, both above 1.884, but lower than nZ of fourmarierite; 2V large. Pleochroism, nX nearly colorless, nY and nZ yellow-orange, dispersion strong $r>v$. Microchemical tests were positive only for Pb, U, and H_2O. Easily loses water when heated. Occurs at only one place in the Shinkolobwe deposits, associated with fourmarierite and diderichite. Named for Adrien Vandendriessche, 1914–1940, Belgian mineralogist.

M.F.

Masuyite

J. F. Vaes, *op. cit.*

Small (0.1 mm.), pseudo-hexagonal, orange-red scales. Orthorhombic, forms: (010), (101), ($\bar{1}$01), (100), and ($\bar{1}$00), with (110) and (111) doubtful. Cleavage (010) perfect. Commonly twinned on (101). Optically biaxial negative, 2V large, nX not observed, $nY=a$ and $nZ=c$ both above nY of curite and below nZ of curite. Microchemical tests were positive for Pb and U; the mineral "is probably hydrated." Occurs in small geodes in pitchblende, Named for Gustave Masuy, died in 1945, who had studied minerals of Belgian Congo.

M.F.

Richetite

J. F. Vaes, *op. cit.*

Small (0.1 mm.), black pseudo-hexagonal plates. Monoclinic, extinction on (010) about 6°, commonly twinned; cleavage (010) perfect, another cleavage perpendicular to (010). Optically biaxial, negative, 2V large; $nX=b$, not measured, nY and nZ are between 2.00 and 2.07. Microchemical tests were positive for Pb and U; H_2O was not tested for because of lack of material. Occurs on needles of uranophane. Named for Emile Richet, died in 1939, formerly Chief Geologist, Union Miniere du Haut-Katanga.

M.F.

Studtite

J. F. Vaes, *op. cit.*

Clear yellow fibrous crystals, several mm. in length and 7–8 microns in width. The fibers are flexible. Orthorhombic. Optically negative, 2V large, *n*X 1.545, *n*Y 1.555, *n*Z 1.68 (parallel to length of fibers). Microchemical tests showed U, a little Pb, water, and carbonate (effervescence with HCl). Occurs with "urophane" (uranophane?) and rutherfordine. Named for F. E. Studt, geologist, who published a geological map of Katanga in 1913.

M.F.

Diderichite

J. F. Vaes, *op. cit.*

Yellow-green fibrous crusts. Orthorhombic. Optically biaxial, positive, 2V large, *n*X above 1.722, below 1.728, *n*Y ± 1.728, *n*Z above 1.728, below 1.74. Microchemical tests showed U, a little water, and carbonate (effervescence with HCl). Named for Norbert Diderich, mining engineer, one of the first to study the Katanga deposits.

Discussion: It is to be regretted that new names were given to these very poorly characterized minerals. The secondary uranium minerals need badly to be re-studied, a very difficult undertaking because of the difficulty of getting enough pure material. Nevertheless, it would be better to hold up publication of descriptions like these until enough data at least were obtained so that future workers could recognize the minerals from the descriptions.

M.F.

Anthoinite

N. Varlamoff, Anthoinite, nouveau tungstate hydrate d'alumine. *Bull. Soc. Geol. Belgique*, **70,** B153-B166 (1947).

Chemical Properties: A hydrate aluminum tungstate, $Al_2O_3 \cdot 2WO_3 \cdot 3H_2O$. Seven analyses (5 complete) gave WO_3 72.50–74.5, Al_2O_3 15.74–17.20, Fe_2O_3 traces to 0.78, H_2O+ 8.70–9.20, with a little SiO_2 and CaO in some analyses. Very slowly attacked by HCl and HNO_3, easily dissolved by strong KOH solution even after it has been heated. Slowly dissolved by ammonium hydroxide; more readily dissolved after it has been heated to 750°.

Physical Properties: White, chalky, adheres to the tongue. Usually massive, but also as indistinct crystals (perhaps pseudomorphs). Hardness 1, sp. gr. about 4.6. Microcrystalline and apparently isotropic.

Occurrence: Occurs in placer concentrates containing cassiterite and wolframite at Mt. Misobo, Kalima mining district, Maniema, Belgian Congo, also associated with ferberite in quartz veins that cut black shales. The ferberite appears to be replacing anthoinite. Also found at Ruanda, Kifuruwe region.

Name: For Raymond Anthoine, mining engineer.

Michael Fleischer

Schuilingite

J. F. Vaes, Description d'un nouveau mineral "La Schuilingite." *Bull. Soc. Geol. Belgique*, **90,** B233-B236 (1947).

Azure-blue needles (0.1–0.15 mm. by 0.03–0.05 mm.) form crusts in crevices of an altered rock. The mineral dissolves with effervescence in HCl and the solution gave tests for Cu and Pb. It is biaxial, negative, indices of refraction above 1.74, lower than 1.93, 2V about 60°, pleochroism weak, $nX = a$, $nY = c$, $nZ = b$. Probably orthorhombic, cleavage

(110) perfect, (100) poor. The locality is not given, but presumably is Belgian Congo. Named for H. J. Schuiling, chief geologist of Union Miniere du Haut-Kantanga.

Discussion: This seems to differ from any described mineral, but such meager data do not warrant naming it.

M.F.

Selenio-vaesite, Selenio-siegenite

J. F. Vaes, Quelques sulfures de Shinkolobwe. *Bull. Soc. Geol. Belgique*, **70,** B227-B232 (1947).

Eight analyses of vaesite, $(Ni_1Co)S_2$, are given; six of these contain selenium (10.10–19.70% Se). Three analyses of siegenite are given; one shows 11.65% Se, also 3.80% Te. The names selenio-vaesite and selenio-siegenite are given to these varieties.

Discussion: These varieties with S:Se about 4:1 should have been described as selenian varieties and these unnecessary names should be abandoned.

M.F.

Paraschoepite

Alfred Schoep and Sadi Stradiot, *Am. Mineral.*, **32,** 344–350 (1947).

Epiianthinite

Alfred Schoep and Sadi Stradiot, *Am. Mineral.*, **32,** 344–350 (1947).

Fairchildite

Charles Milton and J. M. Axelrod, *Am. Mineral.*, **32,** 607–624 (1947).

Buetschliite

Charles Milton and J. M. Axelrod, *Am. Mineral.*, **32,** 607–624 (1947).

Groutite

J. W. Gruner, *Am. Mineral.*, **32,** 654–659 (1947).

DISCREDITED MINERALS

Boksputite (=Bismutite+Massicot)

E. W. Heinrich, *Am. Mineral.*, **32,** 365–366 (1947).

M.F.